



PUBLISHED FOR SISSA BY SPRINGER

RECEIVED: October 3, 2011

ACCEPTED: November 7, 2011

PUBLISHED: November 29, 2011

Measurement of energy flow at large pseudorapidities in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV

The CMS collaboration

E-mail: cms-publication-committee-chair@cern.ch

ABSTRACT: The energy flow, $dE/d\eta$, is studied at large pseudorapidities in proton-proton collisions at the LHC, for centre-of-mass energies of 0.9 and 7 TeV. The measurements are made using the CMS detector in the pseudorapidity range $3.15 < |\eta| < 4.9$, for both minimum-bias events and events with at least two high-momentum jets. The data are compared to various pp Monte Carlo event generators whose theoretical models and input parameter values are sensitive to the energy-flow measurements. Inclusion of multiple-parton interactions in the Monte Carlo event generators is found to improve the description of the energy-flow measurements.

KEYWORDS: Hadron-Hadron Scattering

Contents

1	Introduction	1
2	Experimental apparatus	2
3	Event selection	3
3.1	Minimum-bias events	4
3.2	Dijet events	4
4	Monte Carlo models	4
5	Corrections	6
6	Systematic uncertainties	6
7	Results	8
8	Conclusions	14
	The CMS collaboration	20

1 Introduction

Proton-proton collisions at the Large Hadron Collider (LHC) allow Quantum Chromodynamics (QCD) processes to be investigated through the measurement of the average energy per event (energy flow) in specific angular regions. Such a measurement is useful in examining the complex final states that result from a hadron-hadron interaction. Exploiting the large calorimeter coverage of the Compact Muon Solenoid (CMS) detector allows the energy flow to be measured over a wider range than was accessible in previous analyses.

At the LHC, the accessible fraction x of the proton momentum carried by partons can become very small. At small x , parton densities become large, leading to an increased probability for more than one partonic interaction. The final state resulting from a proton-proton interaction can be described as the superposition of several contributions: the hard interaction, initial-state and final-state radiation, hadrons produced in additional multiple-parton interactions [1–4], and beam-beam remnants resulting from the hadronisation of the partons that did not participate in the hard scatter. The underlying event (UE) is defined as everything except the hard interaction, i.e., multiple-parton interactions, beam-beam remnants, and initial-state and final-state radiation. The UE plays an especially important role at high centre-of-mass energy.

Multiple-parton interactions are not well understood theoretically and a systematic description in QCD remains challenging [5]. Phenomenological approaches to multi-parton

dynamics rely strongly on parameterised models and tuned parameters (tunes) to describe data. Measurements of the UE structure have been performed for central values of the pseudorapidity (η), where $\eta = -\ln[\tan(\theta/2)]$, with θ being the polar angle of the particles with respect to the beam axis [6–8]. The energy flow has been measured previously in $p\bar{p}$ collisions [9] at $\sqrt{s} = 0.2 - 0.9$ TeV, as well as in ep collisions [10]. The extension of the measurements to large pseudorapidities and higher centre-of-mass energies is a challenge for the models since, in this region of phase space, parton showers (initial-state radiation), as well as multiple-parton interactions, are expected to play a significant role.

In this paper, the measurement of the energy flow in the pseudorapidity range $3.15 < |\eta| < 4.9$ is presented. The energy flow in an event is defined as $dE/d\eta = \sum_i E_i/\Delta\eta$, where $\sum_i E_i$ is the summed energy of all charged and neutral particles in the event measured in bins of pseudorapidity, and $\Delta\eta$ is the bin width in η . Two different centre-of-mass energies, 0.9 and 7 TeV, were investigated for two different event classes: minimum-bias events and events with central high-transverse-momenta dijets. The latter are expected to be more sensitive to perturbative QCD phenomena.

This paper is organised as follows: section 2 describes the experimental apparatus, and the event selection is explained in section 3. The main features of the Monte Carlo (MC) event generators used for the comparison with data are presented in section 4. Sections 5 and 6 discuss the corrections and systematic uncertainties related to the energy-flow measurement. The results are presented in section 7, and the final conclusions are summarised in section 8.

2 Experimental apparatus

This section briefly summarises some features of the CMS apparatus relevant for the present measurement. A complete description of the CMS detector can be found elsewhere [11]. The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point (IP), the x axis pointing towards the centre of the LHC ring, the y axis pointing upwards, and the z axis along the anticlockwise-beam direction. The azimuthal angle ϕ is measured with respect to the x axis, in the $x - y$ plane, and the polar angle θ is defined with respect to the z axis.

The central feature of CMS is a superconducting solenoid, of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter and the brass/scintillator hadron calorimeter. The tracker measures charged particle trajectories in the pseudorapidity range $|\eta| < 2.5$.

For triggering purposes, the CMS trigger system [12, 13] was used, together with two elements of the CMS detector monitoring system, the beam scintillation counters (BSC) [14] and the beam Pick-up-timing for the experiments (BPTX) devices [15]. A BSC detector is located on each side of the interaction region, at a distance of 10.86 m from the nominal crossing point, covering the $|\eta|$ range from 3.23 to 4.65. Each BSC consists of a set of 16 scintillator tiles. They provide information on hits and coincidence signals with an average detection efficiency of 96.3% for minimum-ionising particles and a time resolution of 3 ns,

compared to a minimum inter-bunch spacing of 50 ns for collisions. Located around the beam pipe at distances of 175 m on either side of the IP, the two BPTX devices are designed to provide precise information on the structure and timing of the LHC beams, with a time resolution better than 0.2 ns.

For the present analysis, the energy was measured with the hadronic forward (HF) calorimeters, which cover the region $2.9 < |\eta| < 5.2$. The front face of each calorimeter is located 11.2 m from the interaction point, at each end of CMS. The HF calorimeters consist of iron absorbers and embedded radiation-hard quartz fibres, providing a fast collection of the Čerenkov light. The collected light is detected using radiation-hard photomultiplier tubes (PMT). The quartz fibres are grouped into two categories, segmenting the HF calorimeters longitudinally: long fibres, which run over the full depth of the absorber ($165 \text{ cm} \approx 10\lambda_I$), and short fibres, which start at a depth of 22 cm from the front of the detector. Each set of fibres is read out separately. The different lengths of the fibre sets make it possible to distinguish between electromagnetic and hadronic showers.

Calorimeter cells are formed by grouping bundles of fibres. Clusters of these cells (e.g., 3×3 grouping) form a calorimeter tower. There are 13 towers in η , each with a size given by $\Delta\eta \approx 0.175$, except for the lowest- and highest- $|\eta|$ towers with $\Delta\eta \approx 0.1$ and $\Delta\eta \approx 0.3$, respectively. The azimuthal segmentation of all towers is 10° , except for the one at highest- $|\eta|$, which has $\Delta\phi = 20^\circ$.

Corrections were applied to the data in order to account for geometrical non uniformities of the HF calorimeters, due to non sensitive areas. These are caused by mechanical structures of the 20° ϕ -segment assembly, which are not included in the detector simulation. The relevant correction factors for the non uniformities range between 0.98 for the innermost (large η) pseudorapidity segment and 0.90 for the outermost (small η) segment, and were applied to the total energy deposited in each tower.

The calibration of the HF calorimeters is based on test-beam measurements with 100 GeV pions and electrons [16]. For the relative calibration, a ^{60}Co radioactive source was used. The energy-flow analysis was restricted to the pseudorapidity range $3.15 < |\eta| < 4.9$. The lowest and highest $|\eta|$ towers were excluded from the measurement since they were not properly described in the geometry used for the detector simulation. An additional ring of towers was removed from the analysis because it is partially located in the shadow of the electromagnetic endcap calorimeter.

3 Event selection

The data were collected during the first data-taking period of CMS in 2010, corresponding to integrated luminosities of $239 \mu\text{b}^{-1}$ and $206 \mu\text{b}^{-1}$ for the $\sqrt{s} = 0.9$ and 7 TeV samples, respectively. In less than 1% of the events more than one interaction vertex was recorded (pile up). The energy was measured with the HF calorimeters by summing all energy deposits in the HF towers above a threshold of 4 GeV. This threshold, determined from non collision events, was chosen to suppress electronic noise. In addition, events in which particles hit the photomultipliers and cause large signals in the HF calorimeter towers were removed from

the analysis by means of dedicated algorithms. The rejection criteria are based on the topology of energy deposits and the pulse shape/timing of the signals in the HF calorimeters.

3.1 Minimum-bias events

Minimum-bias events were selected by requiring a trigger signal from the two BPTX detectors indicating the presence of both beams crossing the interaction point, coincident with a signal in each of the BSC detectors. At least one reconstructed primary vertex was required, with a z coordinate within 15 cm of the centre of the beam collision region. The vertex was reconstructed in a fit with a minimum of four associated tracks [17]. Beam-induced background events producing an anomalously large number of pixel hits were rejected by requiring that at least 25% of the tracks in events with more than 10 tracks were of high quality. Tracks were considered of high quality when several requirements were fulfilled, such as the normalised χ^2 of the fit, the compatibility with the primary vertex, and the number of hit layers. A detailed description of the high quality criteria can be found in ref. [18].

A large number of single-diffraction events was removed with the BSC trigger requirement. The fraction of events from single- and double-diffractive dissociation remaining in the samples was estimated with a PYTHIA6 MC event sample: 5% (3%) for $\sqrt{s} = 0.9$ TeV (7 TeV). After applying all the selection criteria, 2.8×10^6 and 9.4×10^6 events remained in the $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV data samples, respectively.

3.2 Dijet events

The jets were reconstructed using the anti- k_T jet clustering algorithm [19], with a distance parameter of 0.5. Particle flow objects [20] that combine information from all the CMS sub-detectors were used as input. The reconstructed jets required only small additional energy corrections derived from the PYTHIA6 MC generator and in-situ measurements with photon+jet and dijet events [21]. The contribution of miss-reconstructed jets was kept at a negligible level by means of the procedures discussed in refs. [22, 23].

The dijet event sample used in the analysis was a subset of the minimum-bias sample. For the event selection, the two highest- p_T jets were required to satisfy the condition $|\Delta\phi(jet_1, jet_2) - \pi| < 1.0$, where $\Delta\phi(jet_1, jet_2)$ is the difference in the azimuthal angles of the two jets, and to lie within the central region ($|\eta| < 2.5$). At $\sqrt{s} = 0.9$ TeV ($\sqrt{s} = 7$ TeV), the leading and sub-leading jets were both required to have $p_{T,jet} > 8$ GeV ($p_{T,jet} > 20$ GeV). The requirement on η ensures that the jets are contained in the central region of CMS, outside the acceptance of the HF calorimeters. The requirement on the minimum transverse momentum of the jets was chosen to reconstruct the jets fully efficiently. The threshold choices result in an approximately similar lower limit on the fractional momentum carried by the jets, at both energies. The dijet selection criteria resulted in 1.1×10^4 (1.2×10^4) events in the $\sqrt{s} = 0.9$ TeV ($\sqrt{s} = 7$ TeV) sample.

4 Monte Carlo models

In this section, the main features of the MC models used for comparison with the data are presented, focusing on the implementation and tuning of the UE. Several tunes of the

PYTHIA6 (version 6.420) [24] event generator were used, each one providing a different description of the non diffractive component: D6T [25], DW [25], Pro-Q20 [26], Pro-pT0 [26], Z2, as well as the central Perugia 2011 tune (P11) [27] and the ATLAS minimum-bias tune 1 (AMBT1) [28].

The tunes differ in the choice of flavour, fragmentation, and UE parameters. The latter set of parameters, which are expected to be important for these measurements, includes parameters for the parton showers, cut-off values for the multiple-parton interactions, parameters determining the geometrical overlap between the incoming protons, and probabilities for colour reconnection. Some of the tunes have common flavour and fragmentation parameters, which have been determined using data from LEP. With the exception of the parameter settings in Z2, P11, and AMBT1, which are based on measurements from the LHC, the other PYTHIA6 UE tunes were determined using data from the Tevatron. Tune Z2 is almost identical to tune Z1 [29], only differing in the choice of parton distribution functions. An overview of the tunes can be found in ref. [27].

The P11 and Z2 tunes, as well as PYTHIA8 [30], use a new model [31] where multiple-parton interactions are interleaved with parton showering. The parton distribution functions used are the CTEQ6L [32] set for D6T and Z2, and the CTEQ5L [33] set for the remaining tunes. Hadronisation in PYTHIA is based on the Lund string fragmentation model [34]. Predictions obtained from PYTHIA8 correspond to the default version of the generator, i.e., without prior tuning to data. In contrast to PYTHIA6, in PYTHIA8 the multiple-parton interactions, initial-state and final-state radiation are all interleaved, and hard diffraction has been included.

The HERWIG++ (version 2.5) [35] MC event generator was also used for comparisons with data. It is based on matrix-element calculations similar to those used in PYTHIA. In both generators, the evolution of the parton distributions functions with momentum scale is driven by the DGLAP [36–39] equations. However, HERWIG++ features angular-ordered parton showers and uses cluster fragmentation for the hadronisation. The parameters for the multiple-parton interactions model in HERWIG++ have been tuned independently for different centre-of-mass energies: for the UE and colour reconnections they were tuned to UE and minimum-bias data at $\sqrt{s} = 0.9 \text{ TeV}$ (tune MU900-2) and to UE data at $\sqrt{s} = 7 \text{ TeV}$ (tune UE7-2) [40].

Predictions from the event generator CASCADE [41, 42] are compared to data from the dijet event samples. In contrast to PYTHIA6 and HERWIG++, CASCADE is based on the CCFM [43–46] evolution equation for the initial-state cascade, supplemented with off-shell matrix elements for the hard scattering. Multiple-parton interactions are not implemented in CASCADE.

The DIPSY MC event generator [47] is based on a dipole picture of BFKL [48–50] evolution. It includes multiple-parton interactions and can be used to predict non diffractive final states. Currently, DIPSY is not tuned to experimental data.

Data are also compared to predictions obtained from pp MC event generators used in cosmic-ray physics [51]. EPOS1.99 [52], QGSJETII [53], QGSJET01 [54], and SIBYLL [55] are considered. All models take into consideration contributions from both soft- and hard-parton dynamics and use a multiple-parton interactions model [56]. In general the soft

component is described in terms of the exchange of virtual quasi-particle states (a Pomeron at high energies) as in Gribov's Reggeon field theory [57]. At higher energies and scales, the interaction is described by perturbative QCD (with DGLAP evolution) by an extension of the approach used to describe the soft region. The models were not tuned to LHC data.

5 Corrections

The data were corrected to the stable-particle ($\tau > 10^{-12}$ s) level with the help of bin-by-bin correction factors derived from simulated events generated with the PYTHIA6.4 MC event generator and passed through the CMS detector simulation based on GEANT4 [58]. The position and width of the beam spot in the simulation were adjusted to that determined from the data. The simulated events were processed using the same analysis chain as for collision data. Corrections to the measured data were applied bin-by-bin to account for acceptance, inefficiency, and bin-to-bin migrations due to the detector resolution.

The correction factor for each bin was determined as the average of the correction factors from the PYTHIA6 P0 [27] D6T, DW, Z2, and Pro-Q20 tune predictions. All the tunes described reasonably well the shape of the data before the correction. The deviation from the average was included in the model-dependent systematic uncertainty. The number of selected events in each of the various MC samples were comparable with the data set size.

The correction factors were calculated as the ratio of MC predictions at the stable-particle level and the detector level. At the stable-particle level, the selected particles were required to be in the same pseudorapidity range as that used for the measurements ($3.15 < |\eta| < 4.9$), without any further requirement on their energies. Neutrinos and muons were excluded. In addition, at least one charged particle was required, on each side, within the acceptance of the BSC ($3.9 < |\eta| < 4.4$). This requirement was imposed in order to replicate the use of the BSC triggers in the detector-level analysis chain.

For the analysis of dijet events, the kinematic selection of the dijet system was the same for the stable-particle level and detector-level jets, i.e., $|\eta_{jet}| < 2.5$, $|\Delta\phi(jet_1, jet_2) - \pi| < 1.0$, and $p_{T,jet} > 8$ GeV ($p_{T,jet} > 20$ GeV) for the $\sqrt{s} = 0.9$ TeV ($\sqrt{s} = 7$ TeV) analysis.

The event selection criteria applied at the stable-particle level in the MC simulation are summarized in table 1.

The bin-by-bin correction factors range from 1.6 to 2.0 (1.5 to 2.0) for the $\sqrt{s} = 0.9$ TeV ($\sqrt{s} = 7$ TeV) minimum-bias and dijet data in the four lowest $|\eta|$ bins of the measurement. Because of the larger amount of dead material within the range of the highest- $|\eta|$ bin, the correction factor is larger, 2.5 and 2.2, for the $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV measurements, respectively. The nonlinear behaviour of the HF calorimeters was implemented in the detector simulation and was therefore taken into account in the bin-by-bin correction.

6 Systematic uncertainties

The systematic uncertainties on the energy-flow measurement are summarised in table 2. The total uncertainty for each $|\eta|$ bin was obtained by adding all the uncertainties in quadrature. Depending on the centre-of-mass energy and the event selection, the total

Minimum-bias event selection
$N_{\text{charged particles}} > 0$ in $3.23 < \eta < 4.65$ and $-4.65 < \eta < -3.23$
Dijet event selection
$N_{\text{charged particles}} > 0$ in $3.23 < \eta < 4.65$ and $-4.65 < \eta < -3.23$
$ \eta_{jet} < 2.5$
$ \Delta\phi(jet_1, jet_2) - \pi < 1.0$
$p_{T,jet} > 8 \text{ GeV}$ ($\sqrt{s} = 0.9 \text{ TeV}$)
$p_{T,jet} > 20 \text{ GeV}$ ($\sqrt{s} = 7 \text{ TeV}$)

Table 1. Event selection criteria applied at the stable-particle level in the MC simulation.

Effect	Minimum-bias analysis	Dijet analysis
Energy scale	10%	10%
Channel-to-channel miscalibration	1%	1%
Minimum energy in calorimeter towers	2%	2%
Photomultiplier hits rejection algorithm	3%	3%
Primary vertex z position	1%	1%
Model uncertainty, $\sqrt{s} = 0.9 / 7 \text{ TeV}$	1–3% / 1–2%	4–11% / 12–17%
Non uniformity corrections	0–3%	0–3%
Short-fibre response, $\sqrt{s} = 0.9 / 7 \text{ TeV}$	3–9% / 3–6%	6–18% / 6–8%
Jet energy scale	-	2%
Total, $\sqrt{s} = 0.9 \text{ TeV}$ (7 TeV)	11–15% (12–13%)	13–24% (17–22%)

Table 2. Systematic uncertainties on the energy-flow measurement for the minimum-bias and dijet analyses and their sum. The ranges indicate the variation of the uncertainty within the different $|\eta|$ bins.

systematic uncertainty was found to be 11–15% and 13–22% for the minimum-bias and dijet analyses, respectively. An important systematic effect in the measurement of the forward energy flow is the global energy-scale uncertainty of the HF calorimeters, which was estimated to be 10% using $Z \rightarrow e^+e^-$ events with one electron in the HF calorimeter and the other reconstructed in other subdetectors.

To estimate the effect of channel-to-channel miscalibration of the HF calorimeters, the response per channel was randomly varied between $\pm 10\%$. The resulting energy flow was shifted by less than 1%. To estimate the possible influence of any remaining calorimeter noise, the requirement on the minimum energy deposit in a tower was increased to 4.5 GeV. This resulted in a change in the energy-flow distributions by less than 2%.

Variations of the algorithms used to reject events with abnormal signals in the HF calorimeters, due to particles hitting the photomultipliers, give a systematic uncertainty on the energy flow of approximately 3%.

The pseudorapidity η is defined with respect to the origin of the CMS reference coordinate system. For events with a primary vertex far (e.g., $|z| > 15$ cm) from that point, the distributions of measured variables as a function of η are shifted. To estimate the influence of this effect, the energy flow was calculated separately for events with the primary vertex restricted to the ranges $|z| < 4$ cm, $4 < |z| < 9$ cm and $9 < |z| < 15$ cm. The largest difference was approximately 1%.

The systematic uncertainties due to the model dependence of the bin-by-bin corrections were estimated from the differences between the correction factors obtained from the various MC tunes and the average value. The differences were applied to the data points uniformly. Depending on the centre-of-mass energy and the $|\eta|$ bin, the resulting changes were between 1 and 17%. Possible residual systematic effects resulting from the non linearity of the HF calorimeters arise from the difference in the particle spectra and energy distributions predicted by the various MC tunes. This was also included in the model dependence of the correction factor.

The uncertainty on the non uniformity corrections leads to a systematic uncertainty in the energy flow of approximately 3% for the highest $|\eta|$ bin, and is negligible for the lowest bin.

An additional systematic uncertainty comes from the simulation of the short-fibre response in the HF, determined by repeating the full analyses using the long fibres exclusively. The former was not fully described in the HF simulation at low energies. The resulting uncertainty on the energy-flow measurement was between 3 and 9% for the minimum-bias datasets. For the dijet samples the uncertainty was between 6 and 10%, except for the two highest-pseudorapidity bins for $\sqrt{s} = 0.9$ TeV, where it was between 13 and 18%.

In the case of the dijet data sample, an additional uncertainty arises from the jet energy scale. This was estimated by varying the jet energy by $\pm 10\%$, leading to an uncertainty in the energy flow of 2%.

The contribution of beam-gas and non interaction events to the event sample was investigated by performing the minimum-bias selection on events triggered when there was no beam crossing. It was found that no such event passed the selection criteria. Other sources of systematic effects such as pile up and diffractive modelling were each found to contribute less than 1% to the total systematic uncertainty.

7 Results

The energy flow was measured with the CMS HF calorimeters at large pseudorapidities, $3.15 < |\eta| < 4.9$, and corrected to the stable-particle level. The results are shown in figure 1 for minimum-bias and dijet events, at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV. The systematic uncertainties are indicated as error bars; they are correlated between the $|\eta|$ bins. The statistical errors are negligible. The data are also presented in tables 3 and 4.

We observe three distinct features of the data. The first is that the energy flow in both minimum-bias and dijet events increases with pseudorapidity, and the increase is found to be steeper for minimum-bias events. The second is that the energy flow increases with centre-of-mass energy, being a factor of two to three higher at $\sqrt{s} = 7$ TeV than at $\sqrt{s} = 0.9$ TeV. The increase in energy flow for minimum-bias events is larger than what is observed in the charged-particle multiplicity, $dN_{ch}/d\eta$, reported in ref. [59]. Finally, the average energy flow is significantly higher in dijet events than in the minimum-bias sample.

The data are compared to different MC predictions. In figure 1 (upper) the minimum-bias measurements are compared to the predictions of various PYTHIA6 tunes. An interesting observation is the similarity between the predictions of tunes Z2 and AMBT1, both based on LHC data, and the older D6T tune. Predictions obtained from several other PYTHIA tunes are also shown. The variation of the predictions is on the order of 10–20%.

In figure 2 (upper) the minimum-bias measurements are compared to results from different Monte Carlo event generators. The PYTHIA6 tunes (also shown in figure 1) are presented as a band, which is constructed from the minimum and maximum values of the different PYTHIA6 predictions in each bin. The tunes giving the limits of the bands are different for each bin. Also shown are the predictions of PYTHIA8, HERWIG++, DIPSY, and PYTHIA6 D6T without multiple-parton interactions. The prediction from PYTHIA without multiple-parton interactions is at least 40% lower than the measurement. We checked that the same prediction at the parton level (without hadronisation) gives smaller energy flow, by approximately 20%. We also found that changing the maximum value for the scale used in the parton shower by a factor of four increases the energy flow only by $\sim 5\%$. Therefore, these effects cannot bring the prediction without multiple-parton interactions into agreement with the data. The HERWIG++ tunes describe the measurements well at both centre-of-mass energies. The PYTHIA8 predictions are always within the tune uncertainty band of PYTHIA6 and give a slightly flatter energy flow distribution than the data. DIPSY, without prior tuning, describes the minimum-bias data well for $\sqrt{s} = 7$ TeV. However, it overestimates the energy flow for $\sqrt{s} = 0.9$ TeV, by up to 50%. In figure 3 the measured energy flow is compared to predictions derived from the event generators EPOS, QGSJETII, QGSJET01, and SIBYLL, which are used in cosmic-ray air shower simulations. The description of the minimum bias data by all these models is good.

The results for the energy flow in dijet events are shown in figures 1–3 (lower). The data are the same in the three figures. In general, the rise of the average energy with increasing pseudorapidity is described by all the models, and the agreement with the data is better than in the case of minimum-bias events. The predictions from PYTHIA with different parameter settings for multiple-parton interactions agree with the data, whereas the prediction without multiple-parton interactions is too low. The prediction from CASCADE, which uses a different parton shower evolution, is also too low compared to the data, although slightly higher than the prediction from PYTHIA without multiple-parton interactions. The energy flow obtained from HERWIG++ is in good agreement with the measurement, while that from DIPSY is consistent with the data at $\sqrt{s} = 7$ TeV, but too high at $\sqrt{s} = 0.9$ TeV. The predictions from the cosmic-ray MC generators are very close to the data, as shown in figure 3 (lower). However, a larger deviation is observed in the

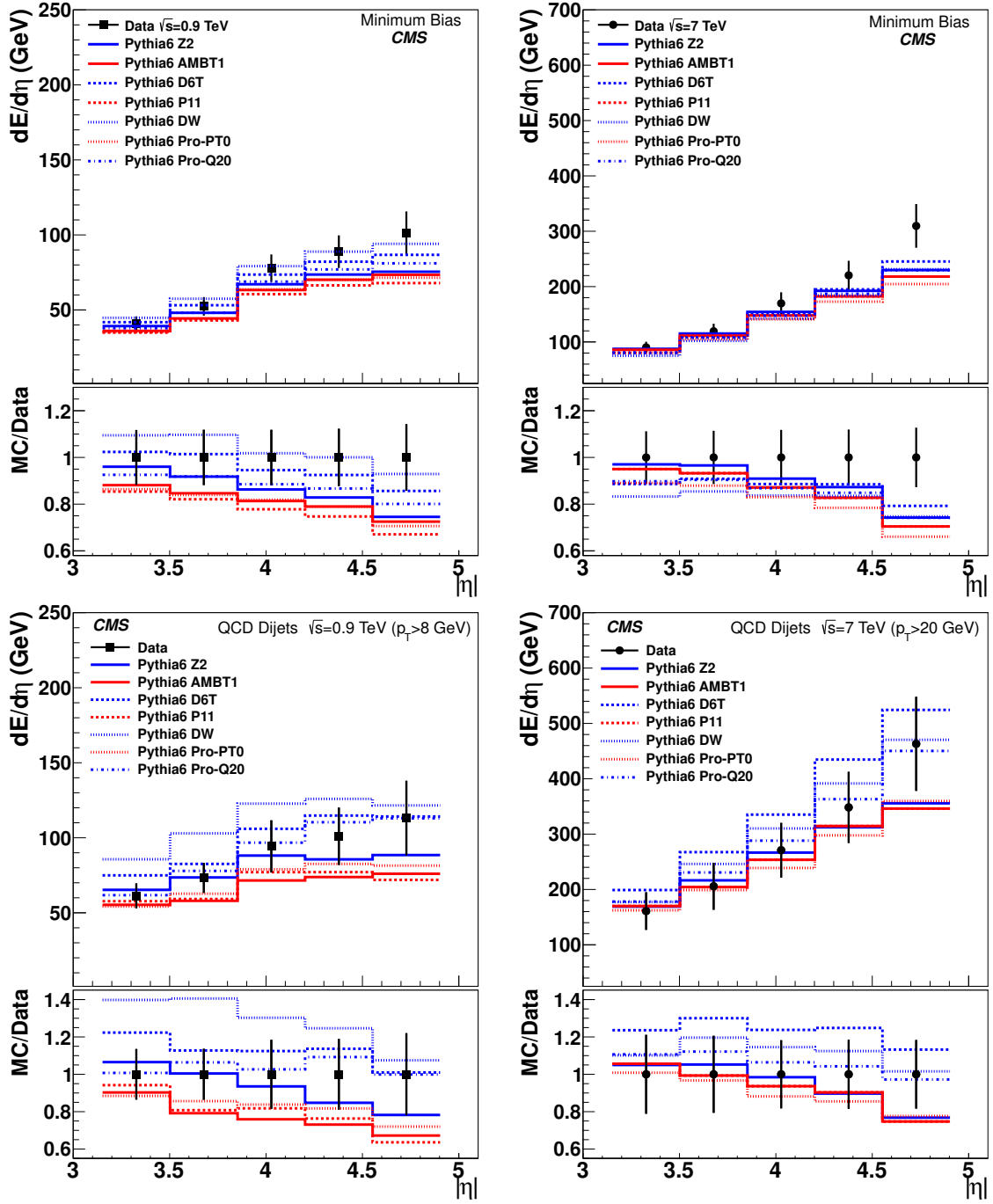


Figure 1. Energy flow as a function of η for minimum-bias (upper) and dijet (lower) events at $\sqrt{s} = 0.9$ and 7 TeV. The data are shown as points with error bars, while the histograms correspond to predictions obtained from various PYTHIA6 tunes. The error bars represent the systematic uncertainties, which are strongly correlated between the bins. The statistical uncertainties are negligible. The lower panels show the ratio of MC prediction to data.

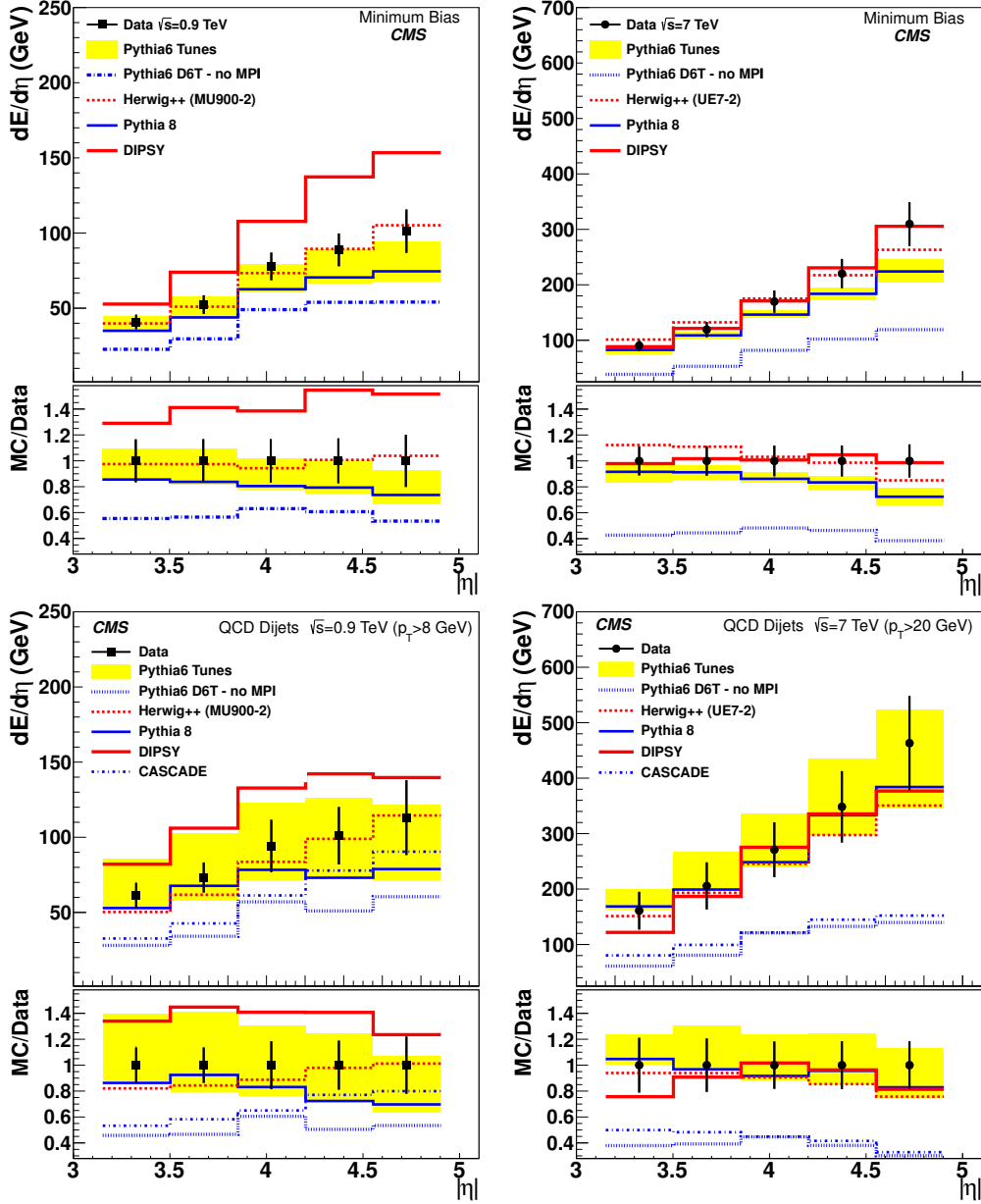


Figure 2. Energy flow as a function of η for minimum-bias (upper) and dijet (lower) events at $\sqrt{s} = 0.9\text{ TeV}$ and $\sqrt{s} = 7\text{ TeV}$. The data are shown as points with error bars, while the histograms correspond to predictions obtained from various Monte Carlo event generators. The yellow bands illustrate the spread of the predictions from the different PYTHIA6 tunes considered. The bands are obtained by taking the minimum and maximum variations of the PYTHIA6 tunes shown in figure 1. The predictions from HERWIG++ are made with tunes specific to the respective centre-of-mass energy. The error bars represent the systematic uncertainties, which are strongly correlated between the bins. The statistical uncertainties are negligible. The lower panels show the ratio of MC prediction to data.

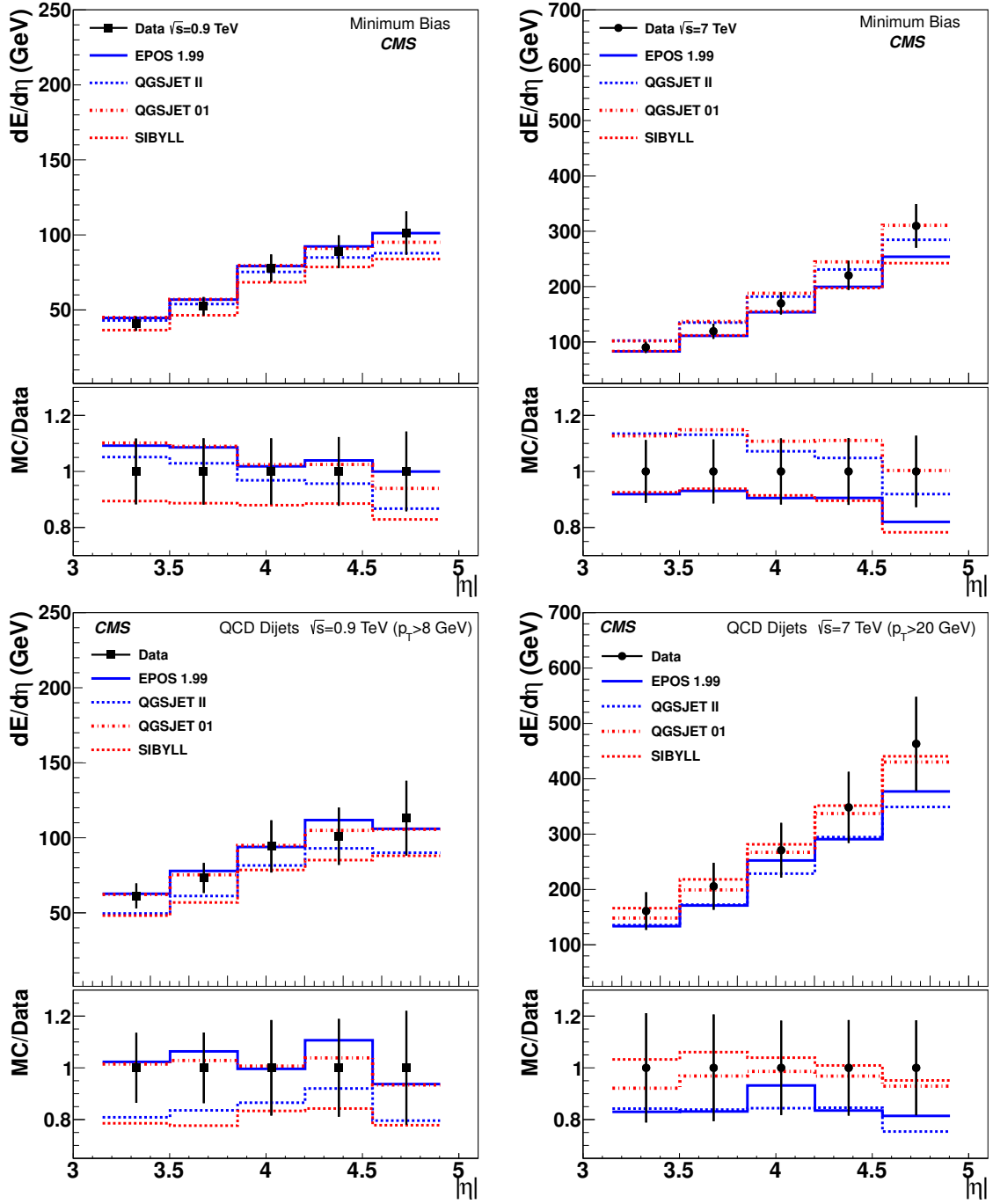


Figure 3. Energy flow as a function of η for minimum-bias (upper) and dijet (lower) events at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV. The data are shown as points with error bars, while the histograms correspond to predictions obtained from different cosmic-ray Monte Carlo event generators. The error bars represent the systematic uncertainties, which are strongly correlated between the bins. The statistical uncertainties are negligible. The lower panels show the ratio of MC prediction to data.

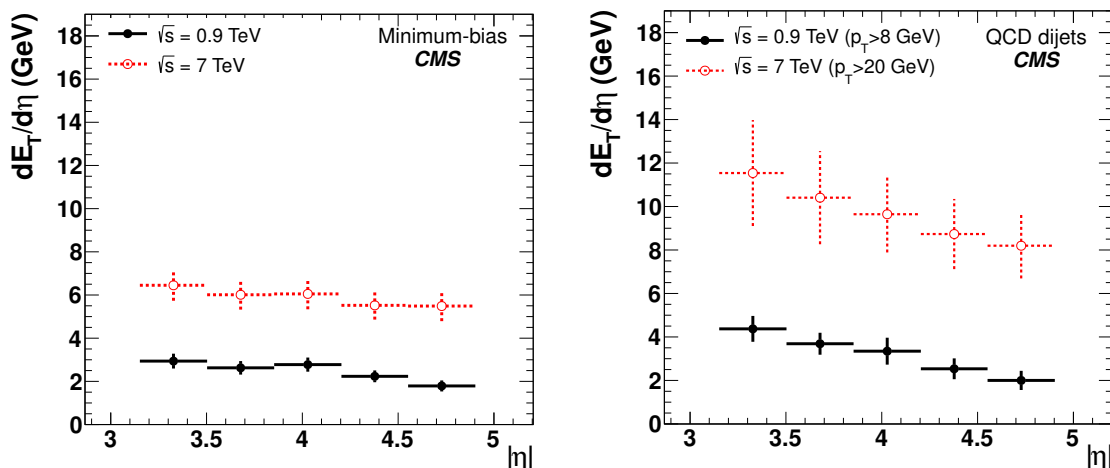


Figure 4. Transverse energy flow as a function of η for minimum-bias and dijet events at $\sqrt{s} = 0.9$ TeV and $\sqrt{s} = 7$ TeV. The data are shown as points with error bars. The error bars represent the systematic uncertainties, which are strongly correlated between the bins. The statistical uncertainties are negligible.

dijet measurement at $\sqrt{s} = 0.9$ TeV, where QGSJETII and SIBYLL underestimate the data in the lowest $|\eta|$ bins, while QGSJET01 is in agreement with the measurement.

We have checked that the energy flow in dijet events, after subtracting the energy flow from minimum-bias events, is still significantly larger than that predicted from MC models without multiple-parton interactions. The disagreement is found to be at least a factor of three. This suggests that the energy flow in dijet events is composed of more than a soft underlying event and a single parton interaction with a parton shower.

From the measured energy flow, we can estimate the transverse energy per pseudorapidity bin i , given by $E_{Ti} = E_i \sin \theta_i$. The increase of the energy flow with increasing pseudorapidity in the minimum-bias events leads to a constant average transverse energy of $dE_T/d\eta \approx 3$ GeV at $\sqrt{s} = 0.9$ TeV rising to $dE_T/d\eta \approx 6$ GeV at $\sqrt{s} = 7$ TeV. The measured transverse energy as a function of pseudorapidity is shown in figure 4. The error bars were obtained by propagating the systematic uncertainties of the energy-flow measurements.

In dijet events the average energy also increases with increasing pseudorapidity, but the increase is less steep than in minimum-bias events, leading to a distribution in E_T that decreases at $\sqrt{s} = 0.9$ TeV from $dE_T/d\eta \approx 4$ GeV at $|\eta| = 3.3$ to ≈ 2 GeV at $|\eta| = 4.7$. At $\sqrt{s} = 7$ TeV the transverse energy decreases from $dE_T/d\eta \approx 11.5$ GeV at $|\eta| = 3.3$ to ≈ 8 GeV at $|\eta| = 4.7$ (figure 4). This decrease of transverse energy is consistent with calculations using a p_T -ordered or virtuality-ordered (Q^2 -ordered) parton evolution, with the highest transverse parton momentum being closest to the hard scatter (at small $|\eta|$), and decreasing towards the direction of the proton (large $|\eta|$). The general behaviour of the energy, as well as the transverse energy flow, is well described by MC models applying a p_T - or virtuality-ordered parton shower with multiple-parton interactions.

	Minimum-bias data			
	$\sqrt{s} = 0.9 \text{ TeV}$		$\sqrt{s} = 7 \text{ TeV}$	
$ \eta $	$dE/d\eta$	δ_{sys}	$dE/d\eta$	δ_{sys}
3.2–3.5	41	5	90	10
3.5–3.9	52	6	119	14
3.9–4.2	78	9	170	20
4.2–4.6	89	11	220	26
4.6–4.9	101	14	310	40

Table 3. Corrected energy flow $dE/d\eta$ and systematic uncertainties δ_{sys} for the minimum-bias measurements. All values are in GeV. The statistical uncertainties are less than 0.1% in all bins, and are therefore not listed.

The average transverse energy measured in dijet events can also be compared to the transverse energy in deep-inelastic scattering (DIS) events measured at HERA [10] at a similar x and Q^2 . We compare our measurement of the transverse energy of $dE_T/d\eta \approx 4 \text{ GeV}$ at $|\eta| = 3.3$ and $\sqrt{s} = 0.9 \text{ TeV}$ (at a scale of $Q^2 = 4p_T^2 \approx 250 \text{ GeV}^2$ and $x \sim 0.02$) with the corresponding value from DIS of $dE_T/d\eta \approx 2 \text{ GeV}$ at $x \sim 0.01$ and $Q^2 \sim 250 \text{ GeV}^2$. For the measurement at 7 TeV, at a scale of $Q^2 = 4p_T^2 = 1600 \text{ GeV}^2$ and $x \sim 0.006$, no corresponding measurements from DIS exist. This comparison shows that the (transverse) energy flow in pp collisions is significantly larger than that measured in DIS, where the contribution from multiple-parton interactions are negligible.

In summary, the shape of the energy-flow distribution, both in minimum-bias and dijet events, is reproduced by all the MC event generators that include a contribution from multiple-parton interactions. However, the magnitude of the average energy density depends significantly on the parameter settings of the different MC tunes. The measured energy flow can thus be used for further constraints on the modeling of multiple-parton interactions.

8 Conclusions

The energy flow at large pseudorapidities, $3.15 < |\eta| < 4.9$, has been measured in pp collisions for minimum-bias events and events with a dijet system in the central region, $|\eta_{jet}| < 2.5$, with $p_{T,jet} > 8 \text{ GeV}$ ($p_{T,jet} > 20 \text{ GeV}$) in pp collisions at $\sqrt{s} = 0.9 \text{ TeV}$ ($\sqrt{s} = 7 \text{ TeV}$).

By requiring a high-momentum dijet in the central region, the deposited energy increases in the entire phase space. Thus the forward energy flow is higher in the dijet data sample than in the minimum-bias sample. The increase of the energy flow with increasing centre-of-mass energy is reproduced in general by all the Monte Carlo event generators, both for minimum-bias and dijet events. The results indicate that predictions of models including multiple-parton interactions are close to the data. The Monte Carlo predictions without multiple-parton interactions, derived from PYTHIA6 and CASCADE, significantly

	Dijet data			
	$\sqrt{s} = 0.9 \text{ TeV}$		$\sqrt{s} = 7 \text{ TeV}$	
$ \eta $	$dE/d\eta$	δ_{sys}	$dE/d\eta$	δ_{sys}
3.2–3.5	61	8	161	34
3.5–3.9	73	10	206	42
3.9–4.2	94	17	271	49
4.2–4.6	101	19	348	64
4.6–4.9	113	25	463	85

Table 4. Corrected energy flow $dE/d\eta$ and systematic uncertainties δ_{sys} for the dijet measurements. All values are in GeV. The statistical errors are less than 0.1% in all bins, and are therefore not listed.

underestimate the energy flow compared to data. None of the PYTHIA6 tunes under study can describe all four energy-flow measurements equally well and, in general, they predict a flatter energy-flow distribution in minimum-bias events. We observe that the D6T and Pro-Q20 tunes provide the best description of the minimum-bias and dijet data, respectively. The predictions from the HERWIG++ tunes as well as DIPSY are also in agreement with the data. The predictions from cosmic-ray interaction models provide the best descriptions of the measured energy flow.

The variation of the energy flow with η , both in minimum-bias and dijet events, is reasonably well reproduced by all Monte Carlo event generators with multiple-parton interactions included. However, the magnitude of the average energy strongly depends on the parameter settings of the different MC tunes, as shown by the large spread in the theoretical predictions.

A comparison with measurements at HERA in deep-inelastic ep collisions, where the contribution from multiple-parton interactions is negligible, shows that the (transverse) energy flow in pp collisions is significantly larger.

Acknowledgments

We would like to thank Tanguy Pierog, Ralph Engel, Sergey Ostapchenko and Ralf Ulrich for providing the predictions of the cosmic-ray MC generators, Simon Plätzer for providing the predictions of Herwig++ and Leif Lönnblad for making the DIPSY predictions available to the CMS collaboration.

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes for their devoted efforts during the design, construction and operation of CMS. The cost of the detectors, computing infrastructure, data acquisition and all other systems without which CMS would not be able to operate was supported by the financing agencies involved in the experiment. We are particularly indebted to: the

Austrian Federal Ministry of Science and Research; the Belgium Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport; the Research Promotion Foundation, Cyprus; the Estonian Academy of Sciences and NICPB; the Academy of Finland, Finnish Ministry of Education, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Office for Research and Technology, Hungary; the Department of Atomic Energy, and Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Korean Ministry of Education, Science and Technology and the World Class University program of NRF, Korea; the Lithuanian Academy of Sciences; the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Pakistan Atomic Energy Commission; the State Commission for Scientific Research, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); the Ministry of Science and Technologies of the Russian Federation, and Russian Ministry of Atomic Energy; the Ministry of Science and Technological Development of Serbia; the Ministerio de Ciencia e Innovacion, and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the National Science Council, Taipei; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation. Individuals have received support from the Marie-Curie IEF program (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; and the Associazione per lo Sviluppo Scientifico e Tecnologico del Piemonte (Italy).

Open Access. This article is distributed under the terms of the Creative Commons Attribution Noncommercial License which permits any noncommercial use, distribution, and reproduction in any medium, provided the original author(s) and source are credited.

References

- [1] T. Sjöstrand and M. van Zijl, *Multiple parton-parton interactions in an impact parameter picture*, *Phys. Lett. B* **188** (1987) 149 [[INSPIRE](#)].
- [2] T. Sjöstrand and M. van Zijl, *A multiple interaction model for the event structure in hadron collisions*, *Phys. Rev. D* **36** (1987) 2019 [[INSPIRE](#)].
- [3] I. Borozan and M. Seymour, *An eikonal model for multiparticle production in hadron hadron interactions*, *JHEP* **09** (2002) 015 [[hep-ph/0207283](#)] [[INSPIRE](#)].

- [4] T. Sjöstrand and P.Z. Skands, *Multiple interactions and the structure of beam remnants*, *JHEP* **03** (2004) 053 [[hep-ph/0402078](#)] [[INSPIRE](#)].
- [5] P. Bartalini and L. Fanó eds., *Multiple partonic interactions at the LHC. Proceedings*, 1st International Workshop, MPI'08, Perugia Italy October 27–31 2008, [DESY-PROC-2009-06](#), DESY, Germany (2009) [[arXiv:1003.4220](#)] [[INSPIRE](#)].
- [6] CDF collaboration, D. Acosta et al., *The underlying event in hard interactions at the Tevatron $p\bar{p}$ collider*, *Phys. Rev. D* **70** (2004) 072002 [[hep-ex/0404004](#)] [[INSPIRE](#)].
- [7] CMS collaboration, V. Khachatryan et al., *First measurement of the underlying event activity at the LHC with $\sqrt{s} = 0.9$ TeV*, *Eur. Phys. J. C* **70** (2010) 555 [[arXiv:1006.2083](#)] [[INSPIRE](#)].
- [8] CMS collaboration, S. Chatrchyan et al., *Measurement of the underlying event activity at the LHC with $\sqrt{s} = 7$ TeV and comparison with $\sqrt{s} = 0.9$ TeV*, [arXiv:1107.0330](#) [[INSPIRE](#)].
- [9] UA1 collaboration, C. Albajar et al., *A study of the general characteristics of $p\bar{p}$ collisions at $\sqrt{s} = 0.2$ TeV to 0.9 TeV*, *Nucl. Phys. B* **335** (1990) 261 [[INSPIRE](#)].
- [10] H1 collaboration, C. Adloff et al., *Measurements of transverse energy flow in deep inelastic scattering at HERA*, *Eur. Phys. J. C* **12** (2000) 595 [[hep-ex/9907027](#)] [[INSPIRE](#)].
- [11] CMS collaboration, *The CMS experiment at the CERN LHC*, 2008 *JINST* **3** S08004 [[INSPIRE](#)].
- [12] CMS collaboration, *CMS physics technical design report volume I: detector performance and software*, [CERN-LHCC-2006-001](#), CERN, Geneva Switzerland (2006).
- [13] CMS collaboration, *Zero bias and HF-based minimum bias triggering for pp collisions at 14 TeV in CMS*, CMS Physics Analysis Summary [PAS-QCD-07-002](#), CERN, Geneva Switzerland (2007).
- [14] A.J. Bell, *The design and construction of the beam scintillation counter for CMS*, Master's thesis, [CERN-THESIS-2009-062](#), Canterbury University, Christchurch New Zealand (2008).
- [15] T. Aumeyr, *Beam phase and intensity monitoring for the Compact Muon Solenoid experiment*, Master's thesis, Vienna University of Technology, Vienna Austria (2008).
- [16] S. Abdullin et al., *Design, performance and calibration of the CMS forward calorimeter wedges*, *Eur. Phys. J. C* **53** (2008) 139 [[INSPIRE](#)].
- [17] CMS collaboration, V. Khachatryan et al., *Transverse momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV*, *JHEP* **02** (2010) 041 [[arXiv:1002.0621](#)] [[INSPIRE](#)].
- [18] CMS collaboration, V. Khachatryan et al., *CMS tracking performance results from early LHC operation*, *Eur. Phys. J. C* **70** (2010) 1165 [[arXiv:1007.1988](#)] [[INSPIRE](#)].
- [19] M. Cacciari, G.P. Salam and G. Soyez, *The anti- k_t jet clustering algorithm*, *JHEP* **04** (2008) 063 [[arXiv:0802.1189](#)] [[INSPIRE](#)].
- [20] CMS collaboration, *Particle-flow event reconstruction in CMS and performance for jets, taus and MET*, CMS Physics Analysis Summary [PAS-PFT-09-001](#), CERN, Geneva Switzerland (2009).
- [21] CMS collaboration, *Jet energy corrections determination at 7 TeV*, CMS Physics Analysis Summary [PAS-JME-10-010](#), CERN, Geneva Switzerland (2010).

- [22] CMS collaboration, *Jets in 0.9 and 2.36 TeV pp collisions*, CMS Physics Analysis Summary [PAS-JME-10-001](#), CERN, Geneva Switzerland (2010).
- [23] CMS collaboration, *Jet performance in pp collisions at 7 TeV*, CMS Physics Analysis Summary [PAS-JME-10-003](#), CERN, Geneva Switzerland (2010).
- [24] T. Sjöstrand et al., *PYTHIA 6.4 physics and manual*, *JHEP* **05** (2006) 026 [[hep-ph/0603175](#)] [[INSPIRE](#)].
- [25] R. Field, *Studying the underlying event at CDF and the LHC*, in *Multiple partonic interactions at the LHC. Proceedings, 1st International Workshop, MPI08*, <http://www-library.desy.de/preparch/desy/proc/proc09-06.pdf>, P. Bartalini and L. Fanó eds., Perugia Italy October 27–31 2008, pg. 12 [[arXiv:1003.4220](#)] [[INSPIRE](#)].
- [26] A. Buckley, H. Hoeth, H. Lacker, H. Schulz and J.E. von Seggern, *Systematic event generator tuning for the LHC*, *Eur. Phys. J. C* **65** (2010) 331 [[arXiv:0907.2973](#)] [[INSPIRE](#)].
- [27] P.Z. Skands, *Tuning Monte Carlo generators: the Perugia tunes*, *Phys. Rev. D* **82** (2010) 074018 [[arXiv:1005.3457](#)] [[INSPIRE](#)].
- [28] ATLAS collaboration, G. Aad et al., *Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC*, *New J. Phys.* **13** (2011) 053033 [[arXiv:1012.5104](#)] [[INSPIRE](#)].
- [29] R. Field, *Early LHC underlying event data — findings and surprises*, [arXiv:1010.3558](#) [[INSPIRE](#)].
- [30] T. Sjöstrand, S. Mrenna and P.Z. Skands, *A brief introduction to PYTHIA 8.1*, *Comput. Phys. Commun.* **178** (2008) 852 [[arXiv:0710.3820](#)] [[INSPIRE](#)].
- [31] P.Z. Skands and D. Wicke, *Non-perturbative QCD effects and the top mass at the Tevatron*, *Eur. Phys. J. C* **52** (2007) 133 [[hep-ph/0703081](#)] [[INSPIRE](#)].
- [32] J. Pumplin et al., *New generation of parton distributions with uncertainties from global QCD analysis*, *JHEP* **07** (2002) 012 [[hep-ph/0201195](#)] [[INSPIRE](#)].
- [33] CTEQ collaboration, H. Lai et al., *Global QCD analysis of parton structure of the nucleon: CTEQ5 parton distributions*, *Eur. Phys. J. C* **12** (2000) 375 [[hep-ph/9903282](#)] [[INSPIRE](#)].
- [34] B. Andersson, G. Gustafson, G. Ingelman and T. Sjöstrand, *Parton fragmentation and string dynamics*, *Phys. Rept.* **97** (1983) 31 [[INSPIRE](#)].
- [35] M. Bahr et al., *HERWIG++ physics and manual*, *Eur. Phys. J. C* **58** (2008) 639 [[arXiv:0803.0883](#)] [[INSPIRE](#)].
- [36] V. Gribov and L. Lipatov, *Deep inelastic ep scattering in perturbation theory*, *Sov. J. Nucl. Phys.* **15** (1972) 438 [[INSPIRE](#)].
- [37] L. Lipatov, *The parton model and perturbation theory*, *Sov. J. Nucl. Phys.* **20** (1975) 94 [[INSPIRE](#)].
- [38] G. Altarelli and G. Parisi, *Asymptotic freedom in parton language*, *Nucl. Phys. B* **126** (1977) 298 [[INSPIRE](#)].
- [39] Y.L. Dokshitzer, *Calculation of the structure functions for deep inelastic scattering and e^+e^- annihilation by perturbation theory in quantum chromodynamics*, *Sov. Phys. JETP* **46** (1977) 641 [[INSPIRE](#)].
- [40] S. Gieseke et al., *HERWIG++ 2.5 release note*, [arXiv:1102.1672](#) [[INSPIRE](#)].

- [41] H. Jung and G. Salam, *Hadronic final state predictions from CCFM: the hadron level Monte Carlo generator CASCADE*, *Eur. Phys. J. C* **19** (2001) 351 [[hep-ph/0012143](#)] [[INSPIRE](#)].
- [42] H. Jung et al., *The CCFM Monte Carlo generator CASCADE 2.2.0*, *Eur. Phys. J. C* **79** (2010) 1237.
- [43] M. Ciafaloni, *Coherence effects in initial jets at small q^2/s* , *Nucl. Phys. B* **296** (1988) 49 [[INSPIRE](#)].
- [44] S. Catani, F. Fiorani and G. Marchesini, *QCD coherence in initial state radiation*, *Phys. Lett. B* **234** (1990) 339 [[INSPIRE](#)].
- [45] S. Catani, F. Fiorani and G. Marchesini, *Small x behavior of initial state radiation in perturbative QCD*, *Nucl. Phys. B* **336** (1990) 18.
- [46] G. Marchesini, *QCD coherence in the structure function and associated distributions at small x* , *Nucl. Phys. B* **445** (1995) 49 [[hep-ph/9412327](#)] [[INSPIRE](#)].
- [47] C. Flensburg, G. Gustafson and L. Lönnblad, *Inclusive and exclusive observables from dipoles in high energy collisions*, [CERN-PH-TH-2011-058](#), CERN, Geneva Switzerland (2011) [[LU-TP-11-13](#)] [[arXiv:1103.4321v1](#)].
- [48] E. Kuraev, L. Lipatov and V.S. Fadin, *Multi-Reggeon processes in the Yang-Mills theory*, *Sov. Phys. JETP* **44** (1976) 443 [[INSPIRE](#)].
- [49] E. Kuraev, L. Lipatov and V.S. Fadin, *The Pomeron singularity in nonabelian gauge theories*, *Sov. Phys. JETP* **45** (1977) 199 [[INSPIRE](#)].
- [50] I. Balitsky and L. Lipatov, *The Pomeron singularity in quantum chromodynamics*, *Sov. J. Nucl. Phys.* **28** (1978) 822 [[INSPIRE](#)].
- [51] D. d'Enterria, R. Engel, T. Pierog, S. Ostapchenko and K. Werner, *Constraints from the first LHC data on hadronic event generators for ultra-high energy cosmic-ray physics*, *Astropart. Phys.* **35** (2011) 98 [[arXiv:1101.5596](#)] [[INSPIRE](#)].
- [52] K. Werner, F.-M. Liu and T. Pierog, *Parton ladder splitting and the rapidity dependence of transverse momentum spectra in deuteron-gold collisions at RHIC*, *Phys. Rev. C* **74** (2006) 044902 [[hep-ph/0506232](#)] [[INSPIRE](#)].
- [53] S. Ostapchenko, *Monte Carlo treatment of hadronic interactions in enhanced Pomeron scheme: I. QGSJET-II model*, *Phys. Rev. D* **83** (2011) 014018 [[arXiv:1010.1869](#)] [[INSPIRE](#)].
- [54] N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov, *Quark-gluon string model and EAS simulation problems at ultra-high energies*, *Nucl. Phys. Proc. Suppl. B* **52** (1997) 17 [[INSPIRE](#)].
- [55] E.-J. Ahn, R. Engel, T.K. Gaisser, P. Lipari and T. Stanev, *Cosmic ray interaction event generator SIBYLL 2.1*, *Phys. Rev. D* **80** (2009) 094003 [[arXiv:0906.4113](#)] [[INSPIRE](#)].
- [56] K. Werner, *Strings, Pomerons and the venus model of hadronic interactions at ultrarelativistic energies*, *Phys. Rept.* **232** (1993) 87 [[INSPIRE](#)].
- [57] V. Gribov, *A Reggeon diagram technique*, *Sov. Phys. JETP* **26** (1968) 414 [[INSPIRE](#)].
- [58] GEANT4 collaboration, S. Agostinelli et al., *GEANT4: a simulation toolkit*, *Nucl. Instrum. Meth. A* **506** (2003) 250 [[INSPIRE](#)].
- [59] CMS collaboration, *Transverse-momentum and pseudorapidity distributions of charged hadrons in pp collisions at $\sqrt{s} = 7$ TeV*, *Phys. Rev. Lett.* **105** (2010) 022002 [[arXiv:1005.3299](#)] [[INSPIRE](#)].

The CMS collaboration

Yerevan Physics Institute, Yerevan, Armenia

S. Chatrchyan, V. Khachatryan, A.M. Sirunyan, A. Tumasyan

Institut für Hochenergiephysik der OeAW, Wien, Austria

W. Adam, T. Bergauer, M. Dragicevic, J. Erö, C. Fabjan, M. Friedl, R. Frühwirth, V.M. Ghete, J. Hammer¹, S. Häseler, M. Hoch, N. Hörmann, J. Hrubec, M. Jeitler, W. Kiesenhofer, M. Krammer, D. Liko, I. Mikulec, M. Pernicka, B. Rahbaran, H. Rohringer, R. Schöfbeck, J. Strauss, A. Taurok, F. Teischinger, P. Wagner, W. Waltenberger, G. Walzel, E. Widl, C.-E. Wulz

National Centre for Particle and High Energy Physics, Minsk, Belarus

V. Mossolov, N. Shumeiko, J. Suarez Gonzalez

Universiteit Antwerpen, Antwerpen, Belgium

S. Bansal, L. Benucci, E.A. De Wolf, X. Janssen, J. Maes, T. Maes, L. Mucibello, S. Ochesanu, B. Roland, R. Rougny, M. Selvaggi, H. Van Haevermaet, P. Van Mechelen, N. Van Remortel

Vrije Universiteit Brussel, Brussel, Belgium

F. Blekman, S. Blyweert, J. D'Hondt, O. Devroede, R. Gonzalez Suarez, A. Kalogeropoulos, M. Maes, W. Van Doninck, P. Van Mulders, G.P. Van Onsem, I. Villella

Université Libre de Bruxelles, Bruxelles, Belgium

O. Charaf, B. Clerbaux, G. De Lentdecker, V. Dero, A.P.R. Gay, G.H. Hammad, T. Hreus, P.E. Marage, L. Thomas, C. Vander Velde, P. Vanlaer

Ghent University, Ghent, Belgium

V. Adler, A. Cimmino, S. Costantini, M. Grunewald, B. Klein, J. Lellouch, A. Marinov, J. McCartin, D. Ryckbosch, F. Thyssen, M. Tytgat, L. Vanelderen, P. Verwilligen, S. Walsh, N. Zaganidis

Université Catholique de Louvain, Louvain-la-Neuve, Belgium

S. Basegmez, G. Bruno, J. Caudron, L. Ceard, E. Cortina Gil, J. De Favereau De Jeneret, C. Delaere, D. Favart, A. Giammanco, G. Grégoire, J. Hollar, V. Lemaitre, J. Liao, O. Militaru, C. Nuttens, S. Ovyn, D. Pagano, A. Pin, K. Piotrkowski, N. Schul

Université de Mons, Mons, Belgium

N. Bely, T. Caebergs, E. Daubie

Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brazil

G.A. Alves, L. Brito, D. De Jesus Damiao, M.E. Pol, M.H.G. Souza

Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil

W.L. Aldá Júnior, W. Carvalho, E.M. Da Costa, C. De Oliveira Martins, S. Fonseca De Souza, D. Matos Figueiredo, L. Mundim, H. Nogima, V. Oguri, W.L. Prado Da Silva, A. Santoro, S.M. Silva Do Amaral, A. Sznajder

Instituto de Fisica Teorica, Universidade Estadual Paulista, Sao Paulo, Brazil

C.A. Bernardes², F.A. Dias, T.R. Fernandez Perez Tomei, E. M. Gregores², C. Lagana, F. Marinho, P.G. Mercadante², S.F. Novaes, Sandra S. Padula

Institute for Nuclear Research and Nuclear Energy, Sofia, Bulgaria

N. Darmenov¹, V. Genchev¹, P. Iaydjiev¹, S. Piperov, M. Rodozov, S. Stoykova, G. Sultanov, V. Tcholakov, R. Trayanov

University of Sofia, Sofia, Bulgaria

A. Dimitrov, R. Hadjiiska, A. Karadzhinova, V. Kozhuharov, L. Litov, M. Mateev, B. Pavlov, P. Petkov

Institute of High Energy Physics, Beijing, China

J.G. Bian, G.M. Chen, H.S. Chen, C.H. Jiang, D. Liang, S. Liang, X. Meng, J. Tao, J. Wang, J. Wang, X. Wang, Z. Wang, H. Xiao, M. Xu, J. Zang, Z. Zhang

State Key Lab. of Nucl. Phys. and Tech., Peking University, Beijing, China

Y. Ban, S. Guo, Y. Guo, W. Li, Y. Mao, S.J. Qian, H. Teng, B. Zhu, W. Zou

Universidad de Los Andes, Bogota, Colombia

A. Cabrera, B. Gomez Moreno, A.A. Ocampo Rios, A.F. Osorio Oliveros, J.C. Sanabria

Technical University of Split, Split, Croatia

N. Godinovic, D. Lelas, K. Lelas, R. Plestina³, D. Polic, I. Puljak

University of Split, Split, Croatia

Z. Antunovic, M. Dzelalija

Institute Rudjer Boskovic, Zagreb, Croatia

V. Brigljevic, S. Duric, K. Kadija, S. Morovic

University of Cyprus, Nicosia, Cyprus

A. Attikis, M. Galanti, J. Mousa, C. Nicolaou, F. Ptochos, P.A. Razis

Charles University, Prague, Czech Republic

M. Finger, M. Finger Jr.

Academy of Scientific Research and Technology of the Arab Republic of Egypt, Egyptian Network of High Energy Physics, Cairo, Egypt

Y. Assran⁴, A. Ellithi Kamel⁵, S. Khalil⁶, M.A. Mahmoud⁷

National Institute of Chemical Physics and Biophysics, Tallinn, Estonia

A. Hektor, M. Kadastik, M. Müntel, M. Raidal, L. Rebane, A. Tiko

Department of Physics, University of Helsinki, Helsinki, Finland

V. Azzolini, P. Eerola, G. Fedi

Helsinki Institute of Physics, Helsinki, Finland

S. Czellar, J. Härkönen, A. Heikkinen, V. Karimäki, R. Kinnunen, M.J. Kortelainen, T. Lampén, K. Lassila-Perini, S. Lehti, T. Lindén, P. Luukka, T. Mäenpää, E. Tuominen, J. Tuominiemi, E. Tuovinen, D. Ungaro, L. Wendland

Lappeenranta University of Technology, Lappeenranta, Finland

K. Banzuzi, A. Karjalainen, A. Korpela, T. Tuuva

Laboratoire d'Annecy-le-Vieux de Physique des Particules, IN2P3-CNRS, Annecy-le-Vieux, France

D. Sillou

DSM/IRFU, CEA/Saclay, Gif-sur-Yvette, France

M. Besancon, S. Choudhury, M. Dejardin, D. Denegri, B. Fabbro, J.L. Faure, F. Ferri, S. Ganjour, F.X. Gentit, A. Givernaud, P. Gras, G. Hamel de Monchenault, P. Jarry, E. Locci, J. Malcles, M. Marionneau, L. Millischer, J. Rander, A. Rosowsky, I. Shreyber, M. Titov, P. Verrecchia

Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

S. Baffioni, F. Beaudette, L. Benhabib, L. Bianchini, M. Bluj⁸, C. Broutin, P. Busson, C. Charlot, T. Dahms, L. Dobrzynski, S. Elgammal, R. Granier de Cassagnac, M. Hagnauer, P. Miné, C. Mironov, C. Ochando, P. Paganini, D. Sabes, R. Salerno, Y. Sirois, C. Thiebaux, B. Wyslouch⁹, A. Zabi

Institut Pluridisciplinaire Hubert Curien, Université de Strasbourg, Université de Haute Alsace Mulhouse, CNRS/IN2P3, Strasbourg, France

J.-L. Agram¹⁰, J. Andrea, D. Bloch, D. Bodin, J.-M. Brom, M. Cardaci, E.C. Chabert, C. Collard, E. Conte¹⁰, F. Drouhin¹⁰, C. Ferro, J.-C. Fontaine¹⁰, D. Gelé, U. Goerlach, S. Greder, P. Juillot, M. Karim¹⁰, A.-C. Le Bihan, Y. Mikami, P. Van Hove

Centre de Calcul de l'Institut National de Physique Nucleaire et de Physique des Particules (IN2P3), Villeurbanne, France

F. Fassi, D. Mercier

Université de Lyon, Université Claude Bernard Lyon 1, CNRS-IN2P3, Institut de Physique Nucléaire de Lyon, Villeurbanne, France

C. Baty, S. Beauceron, N. Beaupere, M. Bedjidian, O. Bondu, G. Boudoul, D. Boumediene, H. Brun, J. Chasserat, R. Chierici, D. Contardo, P. Depasse, H. El Mamouni, J. Fay, S. Gascon, B. Ille, T. Kurca, T. Le Grand, M. Lethuillier, L. Mirabito, S. Perries, V. Sordini, S. Tosi, Y. Tschudi, P. Verdier

Institute of High Energy Physics and Informatization, Tbilisi State University, Tbilisi, Georgia

D. Lomidze

RWTH Aachen University, I. Physikalisches Institut, Aachen, Germany

G. Anagnostou, S. Beranek, M. Edelhoff, L. Feld, N. Heracleous, O. Hindrichs, R. Jussen, K. Klein, J. Merz, N. Mohr, A. Ostapchuk, A. Perieanu, F. Raupach, J. Sammet, S. Schael, D. Sprenger, H. Weber, M. Weber, B. Wittmer

RWTH Aachen University, III. Physikalisches Institut A, Aachen, Germany

M. Ata, E. Dietz-Laursonn, M. Erdmann, T. Hebbeker, C. Heidemann, A. Hinzmann, K. Hoepfner, T. Klimovich, D. Klingebiel, P. Kreuzer, D. Lanske[†], J. Lingemann, C. Magass, M. Merschmeyer, A. Meyer, P. Papacz, H. Pieta, H. Reithler, S.A. Schmitz, L. Sonnenschein, J. Steggemann, D. Teyssier

RWTH Aachen University, III. Physikalisches Institut B, Aachen, Germany

M. Bontenackels, M. Davids, M. Duda, G. Flügge, H. Geenen, M. Giffels, W. Haj Ahmad, D. Heydhausen, F. Hoehle, B. Kargoll, T. Kress, Y. Kuessel, A. Linn, A. Nowack, L. Perchalla, O. Pooth, J. Rennefeld, P. Sauerland, A. Stahl, M. Thomas, D. Tornier, M.H. Zoeller

Deutsches Elektronen-Synchrotron, Hamburg, Germany

M. Aldaya Martin, W. Behrenhoff, U. Behrens, M. Bergholz¹¹, A. Bethani, K. Borras, A. Cakir, A. Campbell, E. Castro, D. Dammann, G. Eckerlin, D. Eckstein, A. Flossdorf, G. Flucke, A. Geiser, J. Hauk, H. Jung¹, M. Kasemann, I. Katkov¹², P. Katsas, C. Kleinwort, H. Kluge, A. Knutsson, M. Krämer, D. Krücker, E. Kuznetsova, W. Lange, W. Lohmann¹¹, R. Mankel, M. Marienfeld, I.-A. Melzer-Pellmann, A.B. Meyer, J. Mnich, A. Mussgiller, J. Olzem, A. Petrukhin, D. Pitzl, A. Raspereza, A. Raval, M. Rosin, R. Schmidt¹¹, T. Schoerner-Sadenius, N. Sen, A. Spiridonov, M. Stein, J. Tomaszewska, R. Walsh, C. Wissing

University of Hamburg, Hamburg, Germany

C. Autermann, V. Blobel, S. Bobrovskiy, J. Draeger, H. Enderle, U. Gebbert, M. Görner, T. Hermanns, K. Kaschube, G. Kaussen, H. Kirschenmann, R. Klanner, J. Lange, B. Mura, S. Naumann-Emme, F. Nowak, N. Pietsch, C. Sander, H. Schettler, P. Schleper, E. Schlieckau, M. Schröder, T. Schum, H. Stadie, G. Steinbrück, J. Thomsen

Institut für Experimentelle Kernphysik, Karlsruhe, Germany

C. Barth, J. Bauer, J. Berger, V. Buege, T. Chwalek, W. De Boer, A. Dierlamm, G. Dirkes, M. Feindt, J. Gruschke, C. Hackstein, F. Hartmann, M. Heinrich, H. Held, K.H. Hoffmann, S. Honc, J.R. Komaragiri, T. Kuhr, D. Martschei, S. Mueller, Th. Müller, M. Niegel, O. Oberst, A. Oehler, J. Ott, T. Peiffer, G. Quast, K. Rabbertz, F. Ratnikov, N. Ratnikova, M. Renz, C. Saout, A. Scheurer, P. Schieferdecker, F.-P. Schilling, G. Schott, H.J. Simonis, F.M. Stober, D. Troendle, J. Wagner-Kuhr, T. Weiler, M. Zeise, V. Zhukov¹², E.B. Ziebarth

Institute of Nuclear Physics "Demokritos", Aghia Paraskevi, Greece

G. Daskalakis, T. Geralis, S. Kesisoglou, A. Kyriakis, D. Loukas, I. Manolakos, A. Markou, C. Markou, C. Mavrommatis, E. Ntomari, E. Petrakou

University of Athens, Athens, Greece

L. Gouskos, T.J. Mertzimekis, A. Panagiotou, E. Stiliaris

University of Ioánnina, Ioánnina, Greece

I. Evangelou, C. Foudas, P. Kokkas, N. Manthos, I. Papadopoulos, V. Patras, F.A. Triantis

KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

A. Aranyi, G. Bencze, L. Boldizsar, C. Hajdu¹, P. Hidas, D. Horvath¹³, A. Kapusi, K. Krajczar¹⁴, F. Sikler¹, G.I. Veres¹⁴, G. Vesztergombi¹⁴

Institute of Nuclear Research ATOMKI, Debrecen, Hungary

N. Beni, J. Molnar, J. Palinkas, Z. Szillasi, V. Veszpremi

University of Debrecen, Debrecen, Hungary

P. Raics, Z.L. Trocsanyi, B. Ujvari

Panjab University, Chandigarh, India

S.B. Beri, V. Bhatnagar, N. Dhingra, R. Gupta, M. Jindal, M. Kaur, J.M. Kohli, M.Z. Mehta, N. Nishu, L.K. Saini, A. Sharma, A.P. Singh, J. Singh, S.P. Singh

University of Delhi, Delhi, India

S. Ahuja, B.C. Choudhary, P. Gupta, S. Jain, A. Kumar, A. Kumar, M. Naimuddin, K. Ranjan, R.K. Shivpuri

Saha Institute of Nuclear Physics, Kolkata, India

S. Banerjee, S. Bhattacharya, S. Dutta, B. Gomber, S. Jain, R. Khurana, S. Sarkar

Bhabha Atomic Research Centre, Mumbai, India

R.K. Choudhury, D. Dutta, S. Kailas, V. Kumar, P. Mehta, A.K. Mohanty¹, L.M. Pant, P. Shukla

Tata Institute of Fundamental Research - EHEP, Mumbai, India

T. Aziz, M. Guchait¹⁵, A. Gurtu, M. Maity¹⁶, D. Majumder, G. Majumder, K. Mazumdar, G.B. Mohanty, A. Saha, K. Sudhakar, N. Wickramage

Tata Institute of Fundamental Research - HECR, Mumbai, India

S. Banerjee, S. Dugad, N.K. Mondal

Institute for Research and Fundamental Sciences (IPM), Tehran, Iran

H. Arfaei, H. Bakhshiansohi¹⁷, S.M. Etesami¹⁸, A. Fahim¹⁷, M. Hashemi, H. Hesari, A. Jafari¹⁷, M. Khakzad, A. Mohammadi¹⁹, M. Mohammadi Najafabadi, S. Paktinat Mehdiabadi, B. Safarzadeh, M. Zeinali¹⁸

INFN Sezione di Bari^a, Università di Bari^b, Politecnico di Bari^c, Bari, Italy

M. Abbrescia^{a,b}, L. Barbone^{a,b}, C. Calabria^{a,b}, A. Colaleo^a, D. Creanza^{a,c}, N. De Filippis^{a,c,1}, M. De Palma^{a,b}, L. Fiore^a, G. Iaselli^{a,c}, L. Lusito^{a,b}, G. Maggi^{a,c}, M. Maggi^a, N. Manna^{a,b}, B. Marangelli^{a,b}, S. My^{a,c}, S. Nuzzo^{a,b}, N. Pacifico^{a,b}, G.A. Pierro^a, A. Pompili^{a,b}, G. Pugliese^{a,c}, F. Romano^{a,c}, G. Roselli^{a,b}, G. Selvaggi^{a,b}, L. Silvestris^a, R. Trentadue^a, S. Tupputi^{a,b}, G. Zito^a

INFN Sezione di Bologna^a, Università di Bologna^b, Bologna, Italy

G. Abbiendi^a, A.C. Benvenuti^a, D. Bonacorsi^a, S. Braibant-Giacomelli^{a,b}, L. Brigliadori^a, P. Capiluppi^{a,b}, A. Castro^{a,b}, F.R. Cavallo^a, M. Cuffiani^{a,b}, G.M. Dallavalle^a, F. Fabbri^a, A. Fanfani^{a,b}, D. Fasanella^a, P. Giacomelli^a, M. Giunta^a, C. Grandi^a, S. Marcellini^a,

G. Masetti^b, M. Meneghelli^{a,b}, A. Montanari^a, F.L. Navarria^{a,b}, F. Odorici^a, A. Perrotta^a, F. Primavera^a, A.M. Rossi^{a,b}, T. Rovelli^{a,b}, G. Siroli^{a,b}, R. Travaglini^{a,b}

INFN Sezione di Catania^a, Università di Catania^b, Catania, Italy

S. Albergo^{a,b}, G. Cappello^{a,b}, M. Chiorboli^{a,b,1}, S. Costa^{a,b}, A. Tricomi^{a,b}, C. Tuve^{a,b}

INFN Sezione di Firenze^a, Università di Firenze^b, Firenze, Italy

G. Barbagli^a, V. Ciulli^{a,b}, C. Civinini^a, R. D'Alessandro^{a,b}, E. Focardi^{a,b}, S. Frosali^{a,b}, E. Gallo^a, S. Gonzi^{a,b}, P. Lenzi^{a,b}, M. Meschini^a, S. Paoletti^a, G. Sguazzoni^a, A. Tropiano^{a,1}

INFN Laboratori Nazionali di Frascati, Frascati, Italy

L. Benussi, S. Bianco, S. Colafranceschi²⁰, F. Fabbri, D. Piccolo

INFN Sezione di Genova, Genova, Italy

P. Fabbriatore, R. Musenich

INFN Sezione di Milano-Bicocca^a, Università di Milano-Bicocca^b, Milano, Italy

A. Benaglia^{a,b}, F. De Guio^{a,b,1}, L. Di Matteo^{a,b}, S. Gennai¹, A. Ghezzi^{a,b}, S. Malvezzi^a, A. Martelli^{a,b}, A. Massironi^{a,b}, D. Menasce^a, L. Moroni^a, M. Paganoni^{a,b}, D. Pedrini^a, S. Ragazzi^{a,b}, N. Redaelli^a, S. Sala^a, T. Tabarelli de Fatis^{a,b}

INFN Sezione di Napoli^a, Università di Napoli "Federico II"^b, Napoli, Italy

S. Buontempo^a, C.A. Carrillo Montoya^{a,1}, N. Cavallo^{a,21}, A. De Cosa^{a,b}, F. Fabozzi^{a,21}, A.O.M. Iorio^{a,1}, L. Lista^a, M. Merola^{a,b}, P. Paolucci^a

INFN Sezione di Padova^a, Università di Padova^b, Università di Trento (Trento)^c, Padova, Italy

P. Azzi^a, N. Bacchetta^a, P. Bellan^{a,b}, D. Bisello^{a,b}, A. Branca^a, R. Carlin^{a,b}, P. Checchia^a, T. Dorigo^a, U. Dosselli^a, F. Fanzago^a, F. Gasparini^{a,b}, U. Gasparini^{a,b}, A. Gozzelino, S. Lacaprara^{a,22}, I. Lazzizzera^{a,c}, M. Margoni^{a,b}, M. Mazzucato^a, A.T. Meneguzzo^{a,b}, M. Nespolo^{a,1}, L. Perrozzi^{a,1}, N. Pozzobon^{a,b}, P. Ronchese^{a,b}, F. Simonetto^{a,b}, E. Torassa^a, M. Tosi^{a,b}, S. Vanini^{a,b}, P. Zotto^{a,b}, G. Zumerle^{a,b}

INFN Sezione di Pavia^a, Università di Pavia^b, Pavia, Italy

P. Baesso^{a,b}, U. Berzano^a, S.P. Ratti^{a,b}, C. Riccardi^{a,b}, P. Torre^{a,b}, P. Vitulo^{a,b}, C. Viviani^{a,b}

INFN Sezione di Perugia^a, Università di Perugia^b, Perugia, Italy

M. Biasini^{a,b}, G.M. Bilei^a, B. Caponeri^{a,b}, L. Fanò^{a,b}, P. Lariccia^{a,b}, A. Lucaroni^{a,b,1}, G. Mantovani^{a,b}, M. Menichelli^a, A. Nappi^{a,b}, F. Romeo^{a,b}, A. Santocchia^{a,b}, S. Taroni^{a,b,1}, M. Valdata^{a,b}

INFN Sezione di Pisa^a, Università di Pisa^b, Scuola Normale Superiore di Pisa^c, Pisa, Italy

P. Azzurri^{a,c}, G. Bagliesi^a, J. Bernardini^{a,b}, T. Boccali^{a,1}, G. Broccolo^{a,c}, R. Castaldi^a, R.T. D'Agnolo^{a,c}, R. Dell'Orso^a, F. Fiori^{a,b}, L. Foà^{a,c}, A. Giassi^a, A. Kraan^a,

F. Ligabue^{a,c}, T. Lomtadze^a, L. Martini^{a,23}, A. Messineo^{a,b}, F. Palla^a, G. Segneri^a, A.T. Serban^a, P. Spagnolo^a, R. Tenchini^a, G. Tonelli^{a,b,1}, A. Venturi^{a,1}, P.G. Verдини^a

INFN Sezione di Roma^a, Università di Roma "La Sapienza"^b, Roma, Italy

L. Barone^{a,b}, F. Cavallari^a, D. Del Re^{a,b}, E. Di Marco^{a,b}, M. Diemoz^a, D. Franci^{a,b}, M. Grassi^{a,1}, E. Longo^{a,b}, P. Meridiani, S. Nourbakhsh^a, G. Organtini^{a,b}, F. Pandolfi^{a,b,1}, R. Paramatti^a, S. Rahatlou^{a,b}, C. Rovelli¹

INFN Sezione di Torino^a, Università di Torino^b, Università del Piemonte Orientale (Novara)^c, Torino, Italy

N. Amapane^{a,b}, R. Arcidiacono^{a,c}, S. Argiro^{a,b}, M. Arneodo^{a,c}, C. Biino^a, C. Botta^{a,b,1}, N. Cartiglia^a, R. Castello^{a,b}, M. Costa^{a,b}, N. Demaria^a, A. Graziano^{a,b,1}, C. Mariotti^a, M. Marone^{a,b}, S. Maselli^a, E. Migliore^{a,b}, G. Mila^{a,b}, V. Monaco^{a,b}, M. Musich^{a,b}, M.M. Obertino^{a,c}, N. Pastrone^a, M. Pelliccioni^{a,b}, A. Potenza^{a,b}, A. Romero^{a,b}, M. Ruspa^{a,c}, R. Sacchi^{a,b}, V. Sola^{a,b}, A. Solano^{a,b}, A. Staiano^a, A. Vilela Pereira^a

INFN Sezione di Trieste^a, Università di Trieste^b, Trieste, Italy

S. Belforte^a, F. Cossutti^a, G. Della Ricca^{a,b}, B. Gobbo^a, D. Montanino^{a,b}, A. Penzo^a

Kangwon National University, Chunchon, Korea

S.G. Heo, S.K. Nam

Kyungpook National University, Daegu, Korea

S. Chang, J. Chung, D.H. Kim, G.N. Kim, J.E. Kim, D.J. Kong, H. Park, S.R. Ro, D.C. Son, T. Son

Chonnam National University, Institute for Universe and Elementary Particles, Kwangju, Korea

J.Y. Kim, Zero J. Kim, S. Song

Korea University, Seoul, Korea

S. Choi, B. Hong, M. Jo, H. Kim, J.H. Kim, T.J. Kim, K.S. Lee, D.H. Moon, S.K. Park, K.S. Sim

University of Seoul, Seoul, Korea

M. Choi, S. Kang, H. Kim, C. Park, I.C. Park, S. Park, G. Ryu

Sungkyunkwan University, Suwon, Korea

Y. Choi, Y.K. Choi, J. Goh, M.S. Kim, J. Lee, S. Lee, H. Seo, I. Yu

Vilnius University, Vilnius, Lithuania

M.J. Bilinskas, I. Grigelionis, M. Janulis, D. Martisiute, P. Petrov, T. Sabonis

Centro de Investigacion y de Estudios Avanzados del IPN, Mexico City, Mexico

H. Castilla-Valdez, E. De La Cruz-Burelo, I. Heredia-de La Cruz, R. Lopez-Fernandez, R. Magaña Villalba, A. Sánchez-Hernández, L.M. Villasenor-Cendejas

Universidad Iberoamericana, Mexico City, Mexico

S. Carrillo Moreno, F. Vazquez Valencia

Benemerita Universidad Autonoma de Puebla, Puebla, Mexico

H.A. Salazar Ibarguen

Universidad Autónoma de San Luis Potosí, San Luis Potosí, Mexico

E. Casimiro Linares, A. Morelos Pineda, M.A. Reyes-Santos

University of Auckland, Auckland, New Zealand

D. Krofcheck, J. Tam

University of Canterbury, Christchurch, New Zealand

P.H. Butler, R. Doesburg, H. Silverwood

National Centre for Physics, Quaid-I-Azam University, Islamabad, Pakistan

M. Ahmad, I. Ahmed, M.I. Asghar, H.R. Hoorani, W.A. Khan, T. Khurshid, S. Qazi

Institute of Experimental Physics, Faculty of Physics, University of Warsaw, Warsaw, Poland

G. Brona, M. Cwiok, W. Dominik, K. Doroba, A. Kalinowski, M. Konecki, J. Krolikowski

Soltan Institute for Nuclear Studies, Warsaw, Poland

T. Frueboes, R. Gokieli, M. Górski, M. Kazana, K. Nawrocki, K. Romanowska-Rybinska, M. Szleper, G. Wrochna, P. Zalewski

Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal

N. Almeida, P. Bargassa, A. David, P. Faccioli, P.G. Ferreira Parracho, M. Gallinaro¹, P. Musella, A. Nayak, J. Pela¹, P.Q. Ribeiro, J. Seixas, J. Varela

Joint Institute for Nuclear Research, Dubna, Russia

S. Afanasiev, I. Belotelov, P. Bunin, I. Golutvin, A. Kamenev, V. Karjavin, G. Kozlov, A. Lanev, P. Moisezenz, V. Palichik, V. Perelygin, S. Shmatov, V. Smirnov, A. Volodko, A. Zarubin

Petersburg Nuclear Physics Institute, Gatchina (St Petersburg), Russia

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, An. Vorobyev

Institute for Nuclear Research, Moscow, Russia

Yu. Andreev, A. Dermenev, S. Gninenko, N. Golubev, M. Kirsanov, N. Krasnikov, V. Matveev, A. Pashenkov, A. Toropin, S. Troitsky

Institute for Theoretical and Experimental Physics, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov[†], M. Kossov¹, A. Krokhotin, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Moscow State University, Moscow, Russia

E. Boos, M. Dubinin²⁴, L. Dudko, A. Ershov, A. Gribushin, O. Kodolova, I. Lokhtin, A. Markina, S. Obraztsov, M. Perfilov, S. Petrushanko, L. Sarycheva, V. Savrin, A. Snigirev

P.N. Lebedev Physical Institute, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

I. Azhgirey, I. Bayshev, S. Bitioukov, V. Grishin¹, V. Kachanov, D. Konstantinov, A. Korablev, V. Krychkine, V. Petrov, R. Ryutin, A. Sobol, L. Tourtchanovitch, S. Troshin, N. Tyurin, A. Uzunian, A. Volkov

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia

P. Adzic²⁵, M. Djordjevic, D. Krpic²⁵, J. Milosevic

Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

M. Aguilar-Benitez, J. Alcaraz Maestre, P. Arce, C. Battilana, E. Calvo, M. Cepeda, M. Cerrada, M. Chamizo Llatas, N. Colino, B. De La Cruz, A. Delgado Peris, C. Diez Pardos, D. Domínguez Vázquez, C. Fernandez Bedoya, J.P. Fernández Ramos, A. Ferrando, J. Flix, M.C. Fouz, P. Garcia-Abia, O. Gonzalez Lopez, S. Goy Lopez, J.M. Hernandez, M.I. Josa, G. Merino, J. Puerta Pelayo, I. Redondo, L. Romero, J. Santaolalla, M.S. Soares, C. Willmott

Universidad Autónoma de Madrid, Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad de Oviedo, Oviedo, Spain

J. Cuevas, J. Fernandez Menendez, S. Folgueras, I. Gonzalez Caballero, L. Lloret Iglesias, J.M. Vizan Garcia

Instituto de Física de Cantabria (IFCA), CSIC-Universidad de Cantabria, Santander, Spain

J.A. Brochero Cifuentes, I.J. Cabrillo, A. Calderon, S.H. Chuang, J. Duarte Campderros, M. Felcini²⁶, M. Fernandez, G. Gomez, J. Gonzalez Sanchez, C. Jorda, P. Lobelle Pardo, A. Lopez Virto, J. Marco, R. Marco, C. Martinez Rivero, F. Matorras, F.J. Munoz Sanchez, J. Piedra Gomez²⁷, T. Rodrigo, A.Y. Rodríguez-Marrero, A. Ruiz-Jimeno, L. Scodellaro, M. Sobron Sanudo, I. Vila, R. Vilar Cortabitarte

CERN, European Organization for Nuclear Research, Geneva, Switzerland

D. Abbaneo, E. Auffray, G. Auzinger, P. Baillon, A.H. Ball, D. Barney, A.J. Bell²⁸, D. Benedetti, C. Bernet³, W. Bialas, P. Bloch, A. Bocci, S. Bolognesi, M. Bona, H. Breuker, K. Bunkowski, T. Camporesi, G. Cerminara, T. Christiansen, J.A. Coarasa Perez, B. Curé, D. D'Enterria, A. De Roeck, S. Di Guida, N. Dupont-Sagorin, A. Elliott-Peisert, B. Frisch, W. Funk, A. Gaddi, G. Georgiou, H. Gerwig, D. Gigi, K. Gill, D. Giordano, F. Glege, R. Gomez-Reino Garrido, M. Gouzevitch, P. Govoni, S. Gowdy, L. Guiducci, M. Hansen, C. Hartl, J. Harvey, J. Hegeman, B. Hegner, H.F. Hoffmann, A. Honma, V. Innocente, P. Janot, K. Kaadze, E. Karavakis, P. Lecoq, C. Lourenço, T. Mäki, M. Malberti,

L. Malgeri, M. Mannelli, L. Masetti, A. Maurisset, F. Meijers, S. Mersi, E. Meschi, R. Moser, M.U. Mozer, M. Mulders, E. Nesvold¹, M. Nguyen, T. Orimoto, L. Orsini, E. Palencia Cortezon, E. Perez, A. Petrilli, A. Pfeiffer, M. Pierini, M. Pimiä, D. Piparo, G. Polese, A. Racz, W. Reece, J. Rodrigues Antunes, G. Rolandi²⁹, T. Rommerskirchen, M. Rovere, H. Sakulin, C. Schäfer, C. Schwick, I. Segoni, A. Sharma, P. Siegrist, P. Silva, M. Simon, P. Sphicas³⁰, M. Spiropulu²⁴, M. Stoye, P. Tropea, A. Tsirou, P. Vichoudis, M. Voutilainen, W.D. Zeuner

Paul Scherrer Institut, Villigen, Switzerland

W. Bertl, K. Deiters, W. Erdmann, K. Gabathuler, R. Horisberger, Q. Ingram, H.C. Kaestli, S. König, D. Kotlinski, U. Langenegger, F. Meier, D. Renker, T. Rohe, J. Sibille³¹, A. Starodumov³²

Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

L. Bäni, P. Bortignon, L. Caminada³³, B. Casal, N. Chanon, Z. Chen, S. Cittolin, G. Dissertori, M. Dittmar, J. Eugster, K. Freudenreich, C. Grab, W. Hintz, P. Lecomte, W. Lustermann, C. Marchica³³, P. Martinez Ruiz del Arbol, P. Milenovic³⁴, F. Moortgat, C. Nägeli³³, P. Nef, F. Nessi-Tedaldi, L. Pape, F. Pauss, T. Punz, A. Rizzi, F.J. Ronga, M. Rossini, L. Sala, A.K. Sanchez, M.-C. Sawley, B. Stieger, L. Tauscher[†], A. Thea, K. Theofilatos, D. Treille, C. Urscheler, R. Wallny, M. Weber, L. Wehrli, J. Weng

Universität Zürich, Zurich, Switzerland

E. Aguilo, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, P. Robmann, A. Schmidt, H. Snoek

National Central University, Chung-Li, Taiwan

Y.H. Chang, K.H. Chen, C.M. Kuo, S.W. Li, W. Lin, Z.K. Liu, Y.J. Lu, D. Mekterovic, R. Volpe, J.H. Wu, S.S. Yu

National Taiwan University (NTU), Taipei, Taiwan

P. Bartalini, P. Chang, Y.H. Chang, Y.W. Chang, Y. Chao, K.F. Chen, W.-S. Hou, Y. Hsiung, K.Y. Kao, Y.J. Lei, R.-S. Lu, J.G. Shiu, Y.M. Tzeng, M. Wang

Cukurova University, Adana, Turkey

A. Adiguzel, M.N. Bakirci³⁵, S. Cerci³⁶, C. Dozen, I. Dumanoglu, E. Eskut, S. Girgis, G. Gokbulut, I. Hos, E.E. Kangal, A. Kayis Topaksu, G. Onengut, K. Ozdemir, S. Ozturk³⁷, A. Polatoz, K. Sogut³⁸, D. Sunar Cerci³⁶, B. Tali³⁶, H. Topakli³⁵, D. Uzun, L.N. Vergili, M. Vergili

Middle East Technical University, Physics Department, Ankara, Turkey

I.V. Akin, T. Aliev, B. Bilin, S. Bilmis, M. Deniz, H. Gamsizkan, A.M. Guler, K. Ocalan, A. Ozpineci, M. Serin, R. Sever, U.E. Surat, E. Yildirim, M. Zeyrek

Bogazici University, Istanbul, Turkey

M. Deliomeroğlu, D. Demir³⁹, E. Gülmez, B. Isildak, M. Kaya⁴⁰, O. Kaya⁴⁰, M. Özbek, S. Ozkorucuklu⁴¹, N. Sonmez⁴²

**National Scientific Center, Kharkov Institute of Physics and Technology,
Kharkov, Ukraine**

L. Levchuk

University of Bristol, Bristol, U.K.

F. Bostock, J.J. Brooke, T.L. Cheng, E. Clement, D. Cussans, R. Frazier, J. Goldstein, M. Grimes, D. Hartley, G.P. Heath, H.F. Heath, L. Kreczko, S. Metson, D.M. Newbold⁴³, K. Nirunpong, A. Poll, S. Senkin, V.J. Smith

Rutherford Appleton Laboratory, Didcot, U.K.

L. Basso⁴⁴, K.W. Bell, A. Belyaev⁴⁴, C. Brew, R.M. Brown, B. Camanzi, D.J.A. Cockerill, J.A. Coughlan, K. Harder, S. Harper, J. Jackson, B.W. Kennedy, E. Olaiya, D. Petyt, B.C. Radburn-Smith, C.H. Shepherd-Themistocleous, I.R. Tomalin, W.J. Womersley, S.D. Worm

Imperial College, London, U.K.

R. Bainbridge, G. Ball, J. Ballin, R. Beuselinck, O. Buchmuller, D. Colling, N. Cripps, M. Cutajar, G. Davies, M. Della Negra, W. Ferguson, J. Fulcher, D. Futyan, A. Gilbert, A. Guneratne Bryer, G. Hall, Z. Hatherell, J. Hays, G. Iles, M. Jarvis, G. Karapostoli, L. Lyons, B.C. MacEvoy, A.-M. Magnan, J. Marrouche, B. Mathias, R. Nandi, J. Nash, A. Nikitenko³², A. Papageorgiou, M. Pesaresi, K. Petridis, M. Pioppi⁴⁵, D.M. Raymond, S. Rogerson, N. Rompotis, A. Rose, M.J. Ryan, C. Seez, P. Sharp, A. Sparrow, A. Tapper, S. Tourneur, M. Vazquez Acosta, T. Virdee, S. Wakefield, N. Wardle, D. Wardrope, T. Whyntie

Brunel University, Uxbridge, U.K.

M. Barrett, M. Chadwick, J.E. Cole, P.R. Hobson, A. Khan, P. Kyberd, D. Leslie, W. Martin, I.D. Reid, L. Teodorescu

Baylor University, Waco, U.S.A.

K. Hatakeyama, H. Liu

The University of Alabama, Tuscaloosa, U.S.A.

C. Henderson

Boston University, Boston, U.S.A.

T. Bose, E. Carrera Jarrin, C. Fantasia, A. Heister, J. St. John, P. Lawson, D. Lazic, J. Rohlf, D. Sperka, L. Sulak

Brown University, Providence, U.S.A.

A. Avetisyan, S. Bhattacharya, J.P. Chou, D. Cutts, A. Ferapontov, U. Heintz, S. Jabeen, G. Kukartsev, G. Landsberg, M. Luk, M. Narain, D. Nguyen, M. Segala, T. Sinthuprasith, T. Speer, K.V. Tsang

University of California, Davis, Davis, U.S.A.

R. Breedon, G. Breto, M. Calderon De La Barca Sanchez, S. Chauhan, M. Chertok, J. Conway, P.T. Cox, J. Dolen, R. Erbacher, E. Friis, W. Ko, A. Kopecky, R. Lander,

H. Liu, S. Maruyama, T. Miceli, M. Nikolic, D. Pellett, J. Robles, S. Salur, T. Schwarz, M. Searle, J. Smith, M. Squires, M. Tripathi, R. Vasquez Sierra, C. Veelken

University of California, Los Angeles, Los Angeles, U.S.A.

V. Andreev, K. Arisaka, D. Cline, R. Cousins, A. Deisher, J. Duris, S. Erhan, C. Farrell, J. Hauser, M. Ignatenko, C. Jarvis, C. Plager, G. Rakness, P. Schlein[†], J. Tucker, V. Valuev

University of California, Riverside, Riverside, U.S.A.

J. Babb, A. Chandra, R. Clare, J. Ellison, J.W. Gary, F. Giordano, G. Hanson, G.Y. Jeng, S.C. Kao, F. Liu, H. Liu, O.R. Long, A. Luthra, H. Nguyen, B.C. Shen[†], R. Stringer, J. Sturdy, S. Sumowidagdo, R. Wilken, S. Wimpenny

University of California, San Diego, La Jolla, U.S.A.

W. Andrews, J.G. Branson, G.B. Cerati, D. Evans, F. Golf, A. Holzner, R. Kelley, M. Lebourgeois, J. Letts, B. Mangano, S. Padhi, C. Palmer, G. Petrucciani, H. Pi, M. Pieri, R. Ranieri, M. Sani, V. Sharma, S. Simon, E. Sudano, M. Tadel, Y. Tu, A. Vartak, S. Wasserbaech⁴⁶, F. Würthwein, A. Yagil, J. Yoo

University of California, Santa Barbara, Santa Barbara, U.S.A.

D. Barge, R. Bellan, C. Campagnari, M. D'Alfonso, T. Danielson, K. Flowers, P. Geffert, J. Incandela, C. Justus, P. Kalavase, S.A. Koay, D. Kovalskyi, V. Krutelyov, S. Lowette, N. Mccoll, V. Pavlunin, F. Rebassoo, J. Ribnik, J. Richman, R. Rossin, D. Stuart, W. To, J.R. Vlimant

California Institute of Technology, Pasadena, U.S.A.

A. Apresyan, A. Bornheim, J. Bunn, Y. Chen, M. Gataullin, Y. Ma, A. Mott, H.B. Newman, C. Rogan, K. Shin, V. Timciuc, P. Traczyk, J. Veverka, R. Wilkinson, Y. Yang, R.Y. Zhu

Carnegie Mellon University, Pittsburgh, U.S.A.

B. Akgun, R. Carroll, T. Ferguson, Y. Iiyama, D.W. Jang, S.Y. Jun, Y.F. Liu, M. Paulini, J. Russ, H. Vogel, I. Vorobiev

University of Colorado at Boulder, Boulder, U.S.A.

J.P. Cumalat, M.E. Dinardo, B.R. Drell, C.J. Edelmaier, W.T. Ford, A. Gaz, B. Heyburn, E. Luigi Lopez, U. Nauenberg, J.G. Smith, K. Stenson, K.A. Ulmer, S.R. Wagner, S.L. Zang

Cornell University, Ithaca, U.S.A.

L. Agostino, J. Alexander, D. Cassel, A. Chatterjee, N. Eggert, L.K. Gibbons, B. Heltsley, K. Henriksson, W. Hopkins, A. Khukhunaishvili, B. Kreis, G. Nicolas Kaufman, J.R. Patterson, D. Puigh, A. Ryd, M. Saelim, E. Salvati, X. Shi, W. Sun, W.D. Teo, J. Thom, J. Thompson, J. Vaughan, Y. Weng, L. Winstrom, P. Wittich

Fairfield University, Fairfield, U.S.A.

A. Biselli, G. Cirino, D. Winn

Fermi National Accelerator Laboratory, Batavia, U.S.A.

S. Abdullin, M. Albrow, J. Anderson, G. Apollinari, M. Atac, J.A. Bakken, L.A.T. Bauerdick, A. Beretvas, J. Berryhill, P.C. Bhat, I. Bloch, F. Borchering, K. Burkett, J.N. Butler, V. Chetluru, H.W.K. Cheung, F. Chlebana, S. Cihangir, W. Cooper, D.P. Eartly, V.D. Elvira, S. Esen, I. Fisk, J. Freeman, Y. Gao, E. Gottschalk, D. Green, O. Gutsche, J. Hanlon, R.M. Harris, J. Hirschauer, B. Hooberman, H. Jensen, M. Johnson, U. Joshi, B. Klima, K. Kousouris, S. Kunori, S. Kwan, C. Leonidopoulos, P. Limon, D. Lincoln, R. Lipton, J. Lykken, K. Maeshima, J.M. Marraffino, D. Mason, P. McBride, T. Miao, K. Mishra, S. Mrenna, Y. Musienko⁴⁷, C. Newman-Holmes, V. O'Dell, R. Pordes, O. Prokofyev, N. Saoulidou, E. Sexton-Kennedy, S. Sharma, W.J. Spalding, L. Spiegel, P. Tan, L. Taylor, S. Tkaczyk, L. Uplegger, E.W. Vaandering, R. Vidal, J. Whitmore, W. Wu, F. Yang, F. Yumiceva, J.C. Yun

University of Florida, Gainesville, U.S.A.

D. Acosta, P. Avery, D. Bourilkov, M. Chen, S. Das, M. De Gruttola, G.P. Di Giovanni, D. Dobur, A. Drozdetskiy, R.D. Field, M. Fisher, Y. Fu, I.K. Furic, J. Gartner, J. Hugon, B. Kim, J. Konigsberg, A. Korytov, A. Kropivnitskaya, T. Kypreos, J.F. Low, K. Matchev, G. Mitselmakher, L. Muniz, C. Prescott, R. Remington, A. Rinkevicius, M. Schmitt, B. Scurlock, P. Sellers, N. Skhirtladze, M. Snowball, D. Wang, J. Yelton, M. Zakaria

Florida International University, Miami, U.S.A.

V. Gaultney, L.M. Lebolo, S. Linn, P. Markowitz, G. Martinez, J.L. Rodriguez

Florida State University, Tallahassee, U.S.A.

T. Adams, A. Askew, J. Bochenek, J. Chen, B. Diamond, S.V. Gleyzer, J. Haas, S. Hagopian, V. Hagopian, M. Jenkins, K.F. Johnson, H. Prosper, L. Quertenmont, S. Sekmen, V. Veeraraghavan

Florida Institute of Technology, Melbourne, U.S.A.

M.M. Baarmand, B. Dorney, S. Guragain, M. Hohlmann, H. Kalakhety, R. Ralich, I. Vodopiyanov

University of Illinois at Chicago (UIC), Chicago, U.S.A.

M.R. Adams, I.M. Anghel, L. Apanasevich, Y. Bai, V.E. Bazterra, R.R. Betts, J. Callner, R. Cavanaugh, C. Dragoiu, L. Gauthier, C.E. Gerber, D.J. Hofman, S. Khalatyan, G.J. Kunde⁴⁸, F. Lacroix, M. Malek, C. O'Brien, C. Silkworth, C. Silvestre, A. Smoron, D. Strom, N. Varelas

The University of Iowa, Iowa City, U.S.A.

U. Akgun, E.A. Albayrak, B. Bilki, W. Clarida, F. Duru, C.K. Lae, E. McCliment, J.-P. Merlo, H. Mermerkaya⁴⁹, A. Mestvirishvili, A. Moeller, J. Nachtman, C.R. Newsom, E. Norbeck, J. Olson, Y. Onel, F. Ozok, S. Sen, J. Wetzel, T. Yetkin, K. Yi

Johns Hopkins University, Baltimore, U.S.A.

B.A. Barnett, B. Blumenfeld, A. Bonato, C. Eskew, D. Fehling, G. Giurgiu, A.V. Gritsan, Z.J. Guo, G. Hu, P. Maksimovic, S. Rappoccio, M. Swartz, N.V. Tran, A. Whitbeck

The University of Kansas, Lawrence, U.S.A.

P. Baringer, A. Bean, G. Benelli, O. Grachov, R.P. Kenny Iii, M. Murray, D. Noonan, S. Sanders, J.S. Wood, V. Zhukova

Kansas State University, Manhattan, U.S.A.

A.F. Barfuss, T. Bolton, I. Chakaberia, A. Ivanov, S. Khalil, M. Makouski, Y. Maravin, S. Shrestha, I. Svintradze, Z. Wan

Lawrence Livermore National Laboratory, Livermore, U.S.A.

J. Gronberg, D. Lange, D. Wright

University of Maryland, College Park, U.S.A.

A. Baden, M. Boutemur, S.C. Eno, D. Ferencek, J.A. Gomez, N.J. Hadley, R.G. Kellogg, M. Kirn, Y. Lu, A.C. Mignerey, K. Rossato, P. Rumerio, F. Santanastasio, A. Skuja, J. Temple, M.B. Tonjes, S.C. Tonwar, E. Twedt

Massachusetts Institute of Technology, Cambridge, U.S.A.

B. Alver, G. Bauer, J. Bendavid, W. Busza, E. Butz, I.A. Cali, M. Chan, V. Dutta, P. Everaerts, G. Gomez Ceballos, M. Goncharov, K.A. Hahn, P. Harris, Y. Kim, M. Klute, Y.-J. Lee, W. Li, C. Loizides, P.D. Luckey, T. Ma, S. Nahn, C. Paus, D. Ralph, C. Roland, G. Roland, M. Rudolph, G.S.F. Stephans, F. Stöckli, K. Sumorok, K. Sung, D. Velicanu, E.A. Wenger, R. Wolf, S. Xie, M. Yang, Y. Yilmaz, A.S. Yoon, M. Zanetti

University of Minnesota, Minneapolis, U.S.A.

S.I. Cooper, P. Cushman, B. Dahmes, A. De Benedetti, P.R. Duder, G. Franzoni, A. Gude, J. Haupt, K. Klapoetke, Y. Kubota, J. Mans, N. Pastika, V. Rekovic, R. Rusack, M. Sasseville, A. Singovsky, N. Tambe

University of Mississippi, University, U.S.A.

L.M. Cremaldi, R. Godang, R. Kroeger, L. Perera, R. Rahmat, D.A. Sanders, D. Summers

University of Nebraska-Lincoln, Lincoln, U.S.A.

K. Bloom, S. Bose, J. Butt, D.R. Claes, A. Dominguez, M. Eads, J. Keller, T. Kelly, I. Kravchenko, J. Lazo-Flores, H. Malbouisson, S. Malik, G.R. Snow

State University of New York at Buffalo, Buffalo, U.S.A.

U. Baur, A. Godshalk, I. Iashvili, S. Jain, A. Kharchilava, A. Kumar, S.P. Shipkowski, K. Smith, J. Zennamo

Northeastern University, Boston, U.S.A.

G. Alverson, E. Barberis, D. Baumgartel, O. Boeriu, M. Chasco, S. Reucroft, J. Swain, D. Trocino, D. Wood, J. Zhang

Northwestern University, Evanston, U.S.A.

A. Anastassov, A. Kubik, N. Odell, R.A. Ofierzynski, B. Pollack, A. Pozdnyakov, M. Schmitt, S. Stoynev, M. Velasco, S. Won

University of Notre Dame, Notre Dame, U.S.A.

L. Antonelli, D. Berry, A. Brinkerhoff, M. Hildreth, C. Jessop, D.J. Karmgard, J. Kolb, T. Kolberg, K. Lannon, W. Luo, S. Lynch, N. Marinelli, D.M. Morse, T. Pearson, R. Ruchti, J. Slaunwhite, N. Valls, M. Wayne, J. Ziegler

The Ohio State University, Columbus, U.S.A.

B. Bylsma, L.S. Durkin, J. Gu, C. Hill, P. Killewald, K. Kotov, T.Y. Ling, M. Rodenburg, G. Williams

Princeton University, Princeton, U.S.A.

N. Adam, E. Berry, P. Elmer, D. Gerbaudo, V. Halyo, P. Hebda, A. Hunt, J. Jones, E. Laird, D. Lopes Pegna, D. Marlow, T. Medvedeva, M. Mooney, J. Olsen, P. Piroué, X. Quan, B. Safdi, H. Saka, D. Stickland, C. Tully, J.S. Werner, A. Zuranski

University of Puerto Rico, Mayaguez, U.S.A.

J.G. Acosta, X.T. Huang, A. Lopez, H. Mendez, S. Oliveros, J.E. Ramirez Vargas, A. Zatserklyaniy

Purdue University, West Lafayette, U.S.A.

E. Alagoz, V.E. Barnes, G. Bolla, L. Borrello, D. Bortoletto, M. De Mattia, A. Everett, A.F. Garfinkel, L. Gutay, Z. Hu, M. Jones, O. Koybasi, M. Kress, A.T. Laasanen, N. Leonardo, C. Liu, V. Maroussov, P. Merkel, D.H. Miller, N. Neumeister, I. Shipsey, D. Silvers, A. Svyatkovskiy, H.D. Yoo, J. Zablocki, Y. Zheng

Purdue University Calumet, Hammond, U.S.A.

P. Jindal, N. Parashar

Rice University, Houston, U.S.A.

C. Boulahouache, K.M. Ecklund, F.J.M. Geurts, B.P. Padley, R. Redjimi, J. Roberts, J. Zabel

University of Rochester, Rochester, U.S.A.

B. Betchart, A. Bodek, Y.S. Chung, R. Covarelli, P. de Barbaro, R. Demina, Y. Eshaq, H. Flacher, A. Garcia-Bellido, P. Goldenzweig, Y. Gotra, J. Han, A. Harel, D.C. Miner, D. Orbaker, G. Petrillo, W. Sakumoto, D. Vishnevskiy, M. Zielinski

The Rockefeller University, New York, U.S.A.

A. Bhatti, R. Ciesielski, L. Demortier, K. Goulios, G. Lungu, S. Malik, C. Mesropian

Rutgers, the State University of New Jersey, Piscataway, U.S.A.

O. Atramentov, A. Barker, D. Duggan, Y. Gershtein, R. Gray, E. Halkiadakis, D. Hidas, D. Hits, A. Lath, S. Panwalkar, R. Patel, K. Rose, S. Schnetzer, S. Somalwar, R. Stone, S. Thomas

University of Tennessee, Knoxville, U.S.A.

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

Texas A&M University, College Station, U.S.A.

R. Eusebi, W. Flanagan, J. Gilmore, A. Gurrola, T. Kamon, V. Khotilovich, R. Montalvo, I. Osipenkov, Y. Pakhotin, J. Pivarski, A. Safonov, S. Sengupta, A. Tatarinov, D. Toback, M. Weinberger

Texas Tech University, Lubbock, U.S.A.

N. Akchurin, C. Bardak, J. Damgov, C. Jeong, K. Kovitanggoon, S.W. Lee, T. Libeiro, P. Mane, Y. Roh, A. Sill, I. Volobouev, R. Wigmans, E. Yazgan

Vanderbilt University, Nashville, U.S.A.

E. Appelt, E. Brownson, D. Engh, C. Florez, W. Gabella, M. Issah, W. Johns, P. Kurt, C. Maguire, A. Melo, P. Sheldon, B. Snook, S. Tuo, J. Velkovska

University of Virginia, Charlottesville, U.S.A.

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, J. Goodell, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

Wayne State University, Detroit, U.S.A.

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Miltène, A. Sakharov

University of Wisconsin, Madison, U.S.A.

M. Anderson, M. Bachtis, J.N. Bellinger, D. Carlsmith, S. Dasu, J. Efron, L. Gray, K.S. Grogg, M. Grothe, R. Hall-Wilton, M. Herndon, A. Hervé, P. Klabbers, J. Klukas, A. Lanaro, C. Lazaridis, J. Leonard, R. Loveless, A. Mohapatra, F. Palmonari, D. Reeder, I. Ross, A. Savin, W.H. Smith, J. Swanson, M. Weinberg

[†]Deceased

¹Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland

²Also at Universidade Federal do ABC, Santo Andre, Brazil

³Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

⁴Also at Suez Canal University, Suez, Egypt

⁵Also at Cairo University, Cairo, Egypt

⁶Also at British University, Cairo, Egypt

⁷Also at Fayoum University, El-Fayoum, Egypt

⁸Also at Soltan Institute for Nuclear Studies, Warsaw, Poland

⁹Also at Massachusetts Institute of Technology, Cambridge, U.S.A.

¹⁰Also at Université de Haute-Alsace, Mulhouse, France

¹¹Also at Brandenburg University of Technology, Cottbus, Germany

¹²Also at Moscow State University, Moscow, Russia

¹³Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary

¹⁴Also at Eötvös Loránd University, Budapest, Hungary

¹⁵Also at Tata Institute of Fundamental Research - HECR, Mumbai, India

¹⁶Also at University of Visva-Bharati, Santiniketan, India

¹⁷Also at Sharif University of Technology, Tehran, Iran

¹⁸Also at Isfahan University of Technology, Isfahan, Iran

- ¹⁹Also at Shiraz University, Shiraz, Iran
- ²⁰Also at Facoltà Ingegneria Università di Roma, Roma, Italy
- ²¹Also at Università della Basilicata, Potenza, Italy
- ²²Also at Laboratori Nazionali di Legnaro dell' INFN, Legnaro, Italy
- ²³Also at Università degli studi di Siena, Siena, Italy
- ²⁴Also at California Institute of Technology, Pasadena, U.S.A.
- ²⁵Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia
- ²⁶Also at University of California, Los Angeles, Los Angeles, U.S.A.
- ²⁷Also at University of Florida, Gainesville, U.S.A.
- ²⁸Also at Université de Genève, Geneva, Switzerland
- ²⁹Also at Scuola Normale e Sezione dell' INFN, Pisa, Italy
- ³⁰Also at University of Athens, Athens, Greece
- ³¹Also at The University of Kansas, Lawrence, U.S.A.
- ³²Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
- ³³Also at Paul Scherrer Institut, Villigen, Switzerland
- ³⁴Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
- ³⁵Also at Gaziosmanpasa University, Tokat, Turkey
- ³⁶Also at Adiyaman University, Adiyaman, Turkey
- ³⁷Also at The University of Iowa, Iowa City, U.S.A.
- ³⁸Also at Mersin University, Mersin, Turkey
- ³⁹Also at Izmir Institute of Technology, Izmir, Turkey
- ⁴⁰Also at Kafkas University, Kars, Turkey
- ⁴¹Also at Suleyman Demirel University, Isparta, Turkey
- ⁴²Also at Ege University, Izmir, Turkey
- ⁴³Also at Rutherford Appleton Laboratory, Didcot, U.K.
- ⁴⁴Also at School of Physics and Astronomy, University of Southampton, Southampton, U.K.
- ⁴⁵Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy
- ⁴⁶Also at Utah Valley University, Orem, U.S.A.
- ⁴⁷Also at Institute for Nuclear Research, Moscow, Russia
- ⁴⁸Also at Los Alamos National Laboratory, Los Alamos, U.S.A.
- ⁴⁹Also at Erzincan University, Erzincan, Turkey